In-Water Ship Hull Inspection with Smart Underwater Robots

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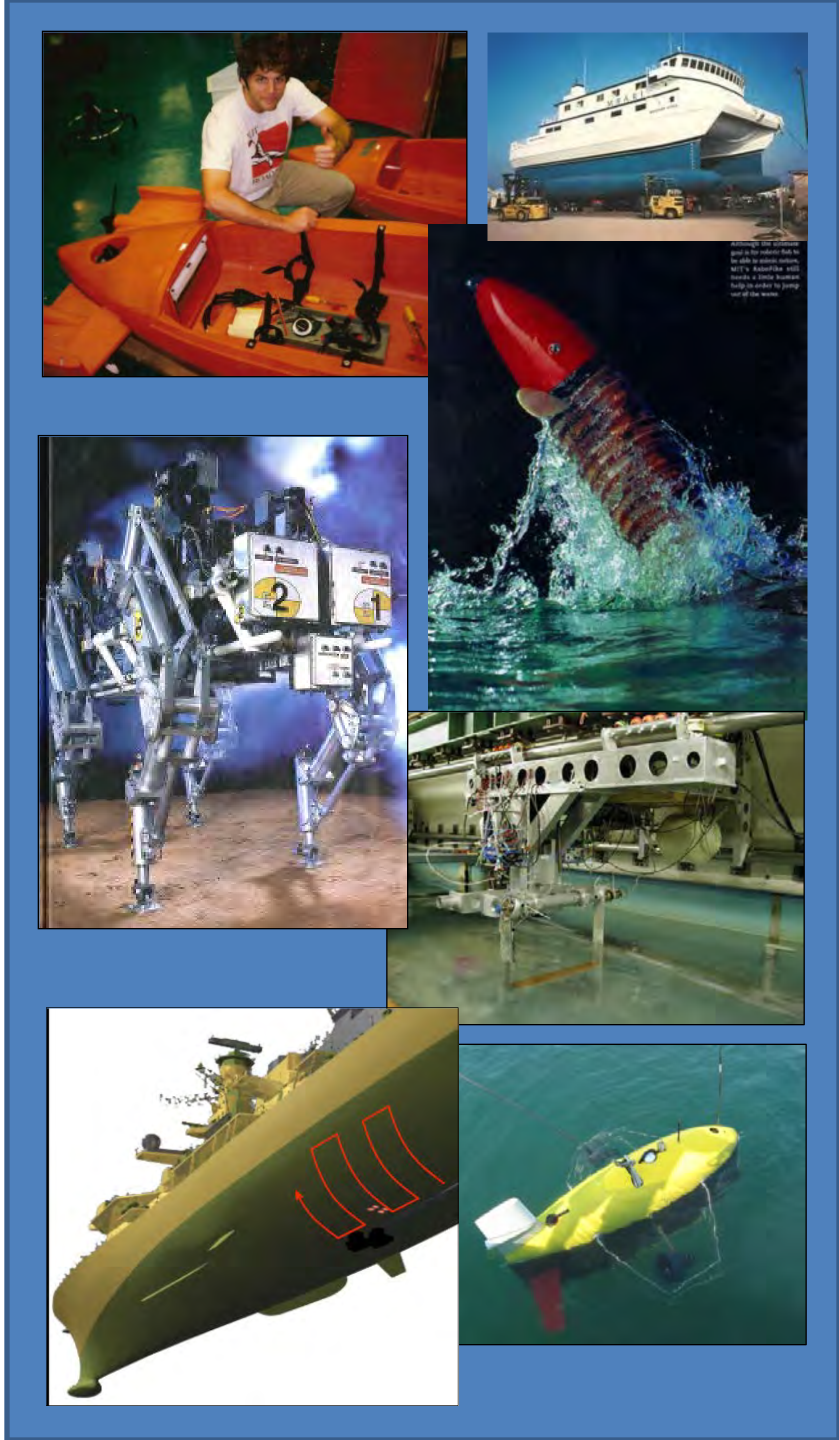
Prescribed by ANSI Std Z39-18

My Background

- BSME Ohio Northern University
- SM & ScD MIT/WHOI Joint Program Oceanographic & Mechanical Engineering
- Post-doc at Monterey Bay Aquarium Research Institute

- **Consultant to Disney, BAE Systems, etc. –**
  design and control, robotics
- **MIT Research Engineer –**
  fluid mechanics, biomimetics, underwater vehicles
- **MIT Assistant Professor –**
  marine robots, electric ship,
  <u>*design problems*</u>



Extraordinary Challenges in Marine Systems for US Navy, Offshore Oil & Gas, Ocean Science, etc.

- *Setting:*
  - *Large physical disturbances;*
  - *Autonomy at all scales due to huge domain;*
  - *Dependence on poor acoustic channel;*
  - *Limited on-board energy, biofouling, fouling, traffic, water pressure, etc.*
- Robotic Systems: autonomy and planning; high number of agents; integrated mission
- Electric Ship: a micro-grid with dynamic loading, and damage scenarios
- MY LONG-TERM GOAL: New Design Principles for Complex Systems in the Marine Environment

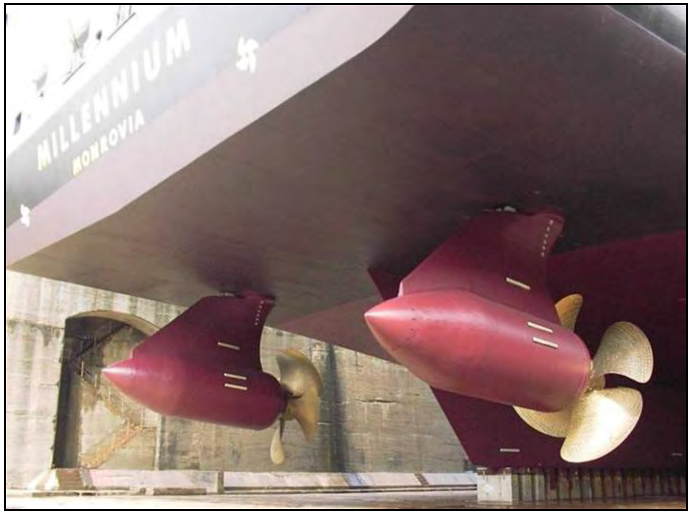
Active Efforts in My Group

- Relaxations and approximations in DC/AC power system design; spectral description of flow networks *(J. Taylor)*
- **Ship Hull Inspection Algorithms and Experiments**
  (B. Englot, H. Johannsson, M. Kaess, with J. Leonard)
- Design rules based on asymptotic random graph models

- Marine Devices:
  - vertical glider for precision seafloor delivery,
  - safety valve for flow control down-hole,
  - low-cost acoustic modems,
  - quadrotors for HAB outbreaks.

All-Electric Ship

ALSTOM Advanced Induction Motor



Tractor podded propulsors

Navy's class of Type 45 Destroyers

QEII

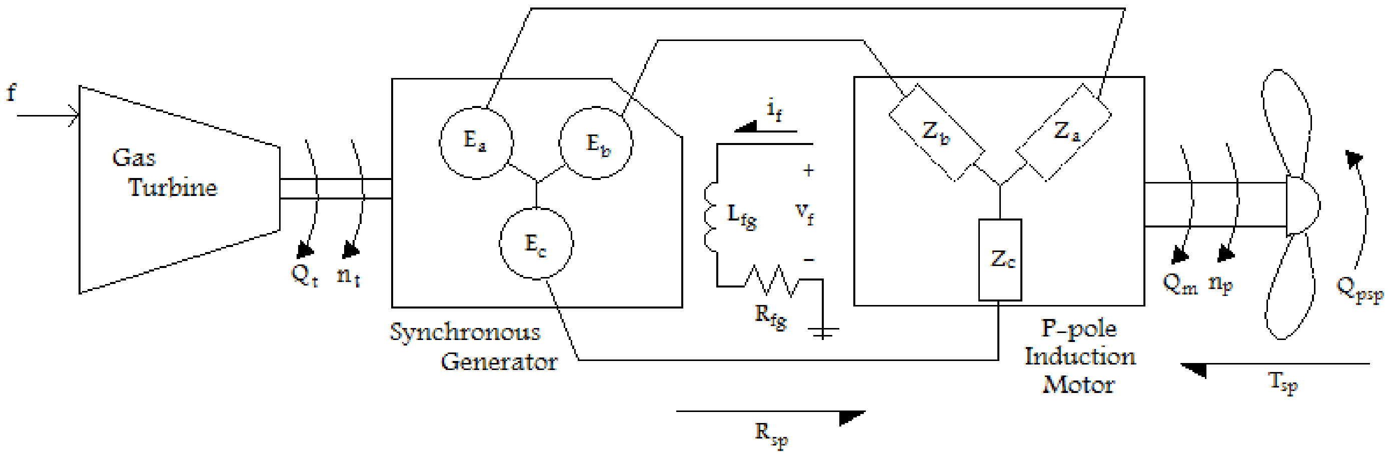
Simple Electric Ship Reference Model with **Complex** Dynamics

Seven-state nonlinear dynamical system

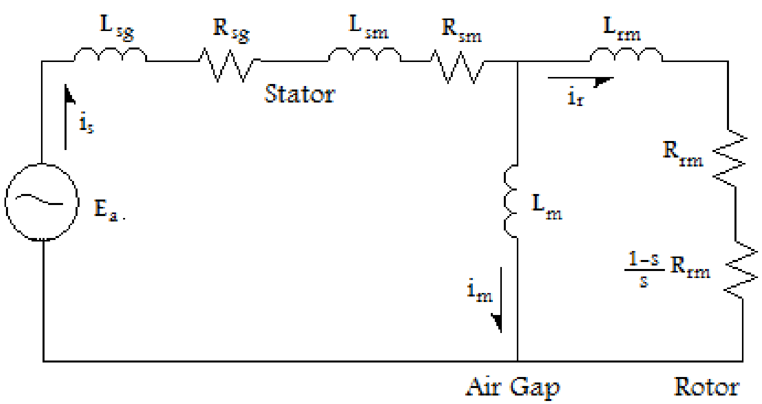
Fully coupled states

Stiff equations; wide range of time constants

Mechanical, hydrodynamic, and electric constitutive equations



Three-Phase Propulsion System



Add controllers, user interface, monitoring s/w, instrumentation, etc….!

Some Key Design Challenges:
Robustness to Attack/Damage,
Reconfiguration,
Very Expensive Simulations
vs. Scalability of Designs

K. Schmitt, MIT

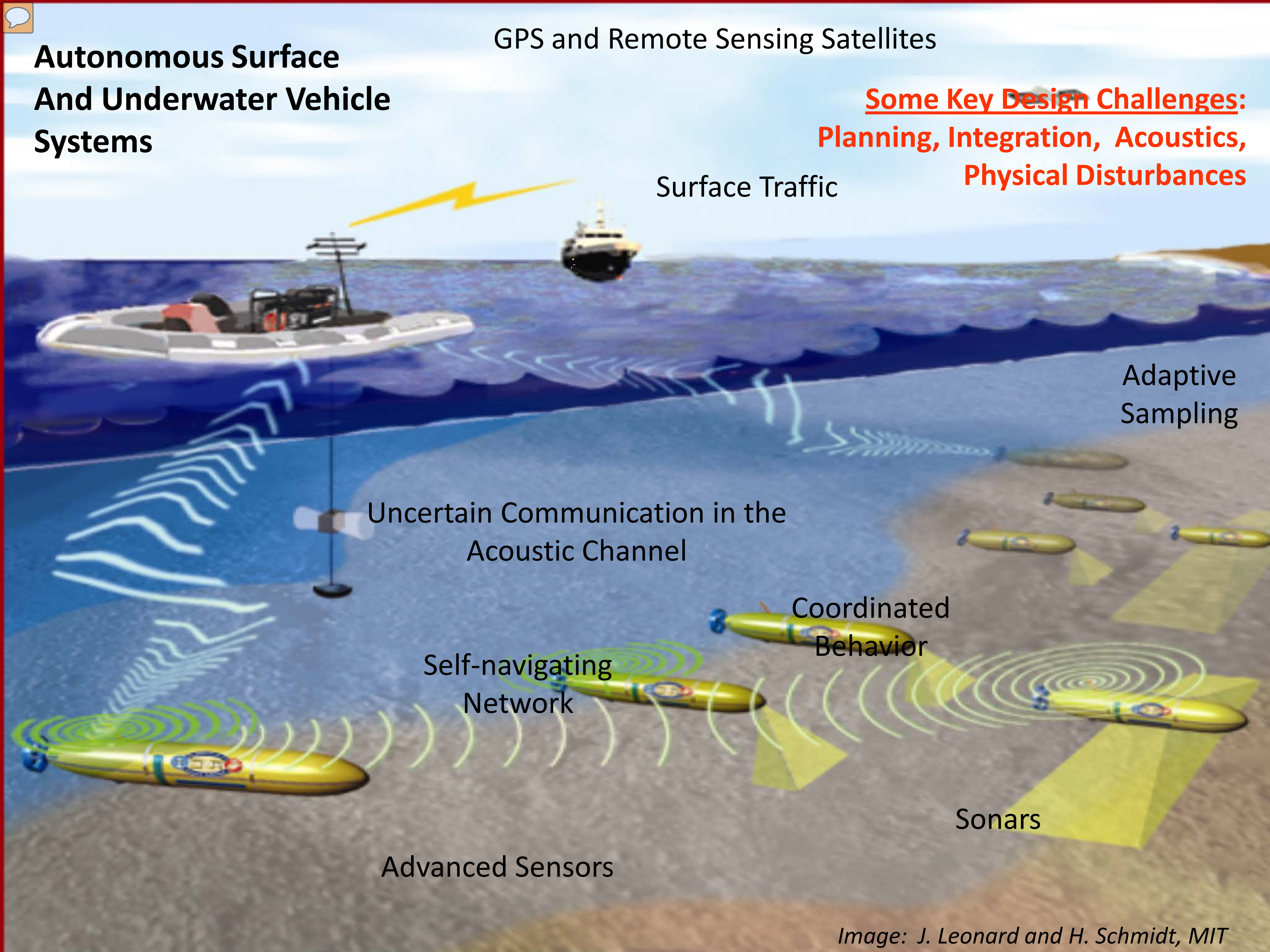
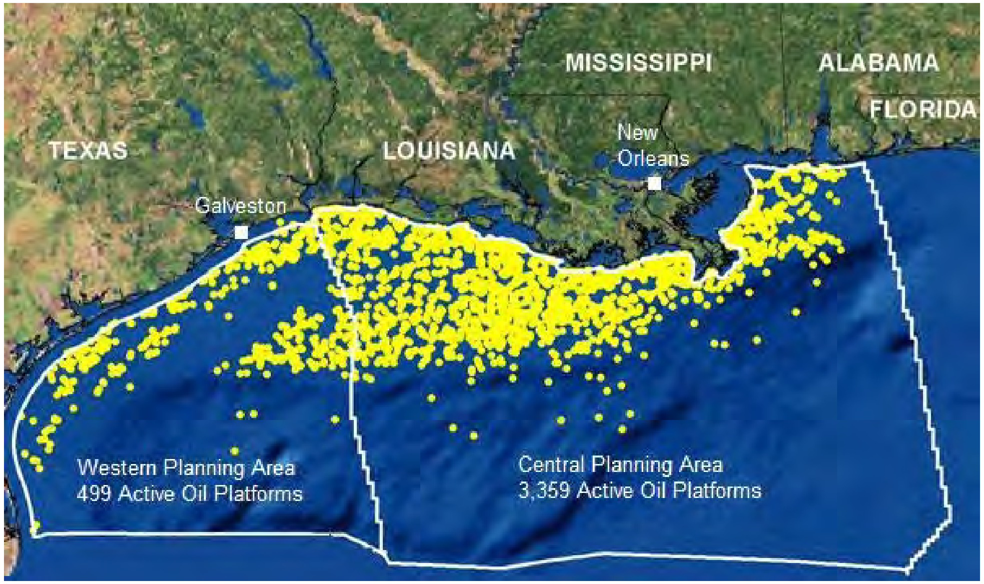


Image: J. Leonard and H. Schmidt, MIT

Offshore Tasks for Autonomous Systems

- Instrument delivery/recovery
- Routine inspection
- Repair
- In-water decommissioning (!)

ngoilgas.com

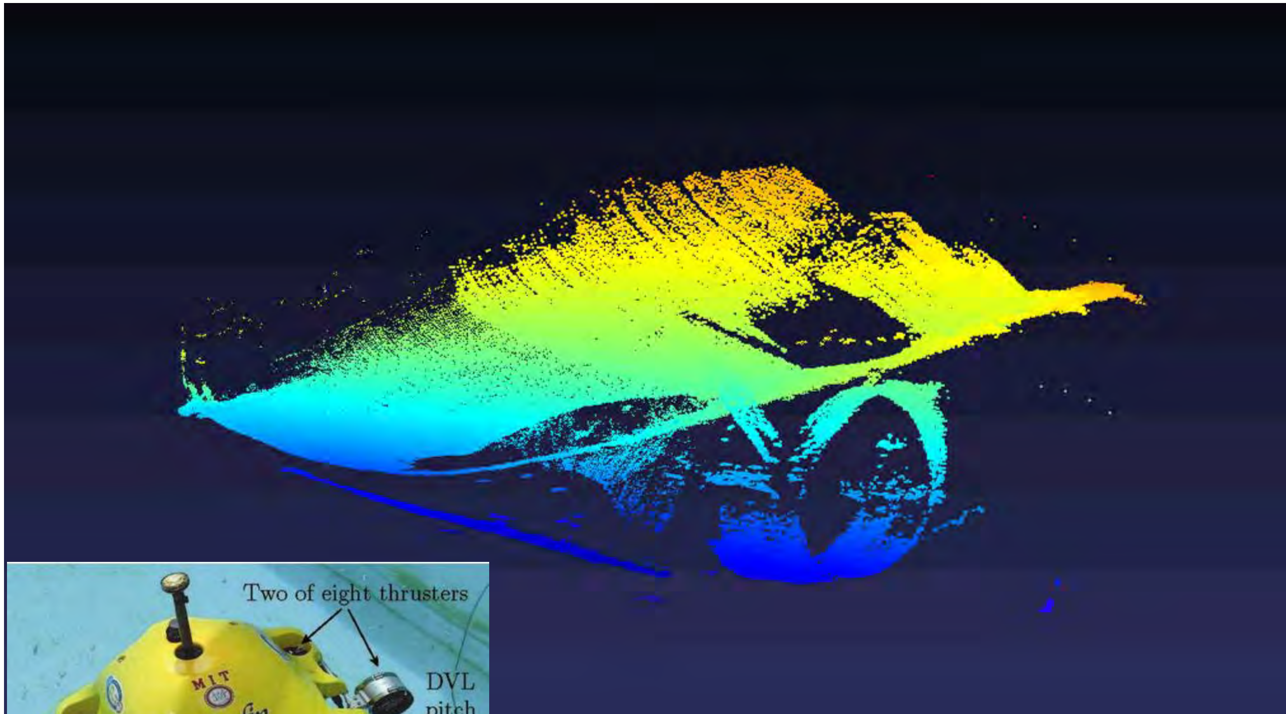


www2.swaylocks.com

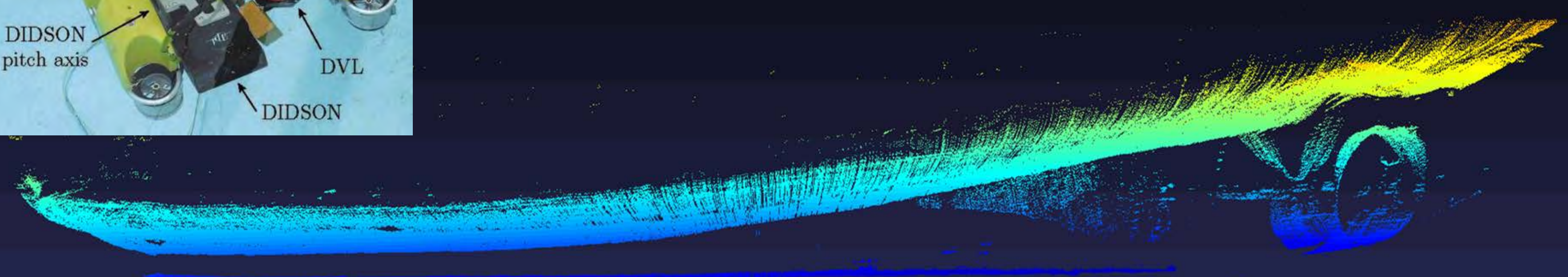
saferenvironment.wordpress.com

R/V Oceanus at WHOI

HAUV imaging with the Blueview "Microbathymetry Blazed Array" Sonar



SN's 4-18 ordered!



← 1. "Non-complex" area → ← 2. "Complex" area →

H. Johannsson, MIT

In-Water Ship Hull Inspection with Autonomous Robots

1. The Objective and its Components

   The task forms a rich and important robotics problem that spans several disciplines

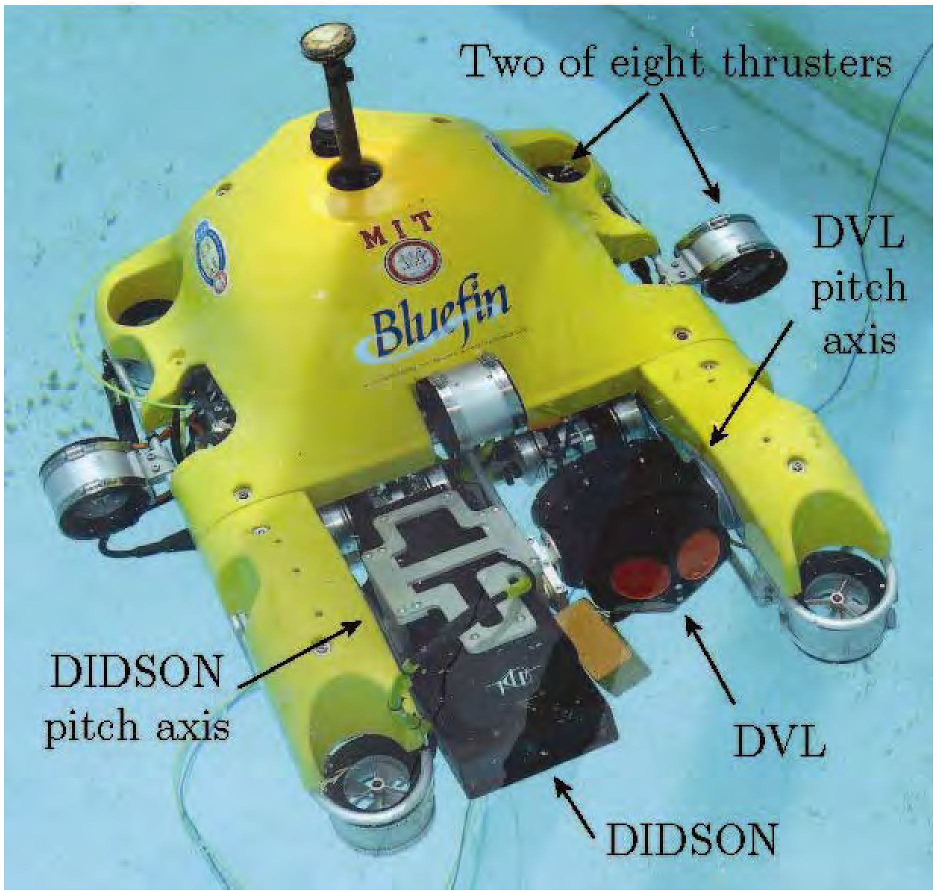
2. Non-complex areas: Feature-Based Nav

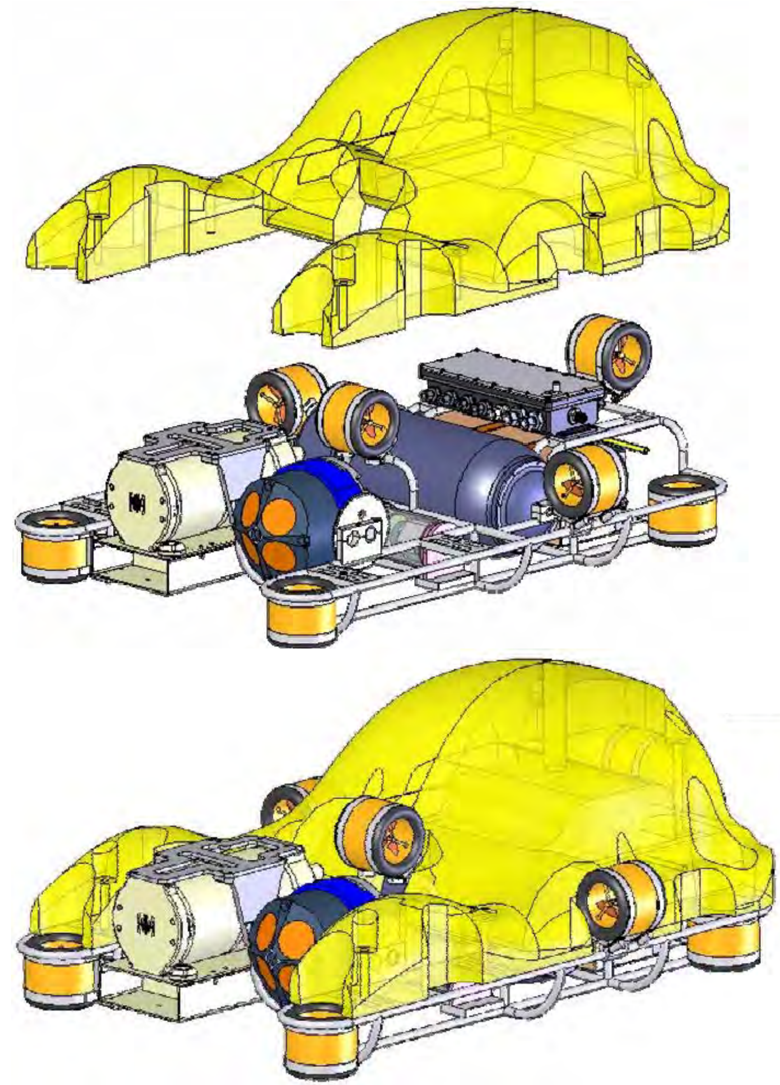
   Sonar and visual imagery both have a key role in building maps and navigating with them

3. Complex areas: Feature-Based Planning

   Guaranteed approximation algorithms to a covering tour problem can provide practical plans quickly

HAUV1B: Built to work close-in





DIDSON: Imaging/Profiling Sonar
DVL : Doppler odometry plus four ranges

M. Kokko, MIT

Heritage:

Harris and Slate 1999: Lamp Ray

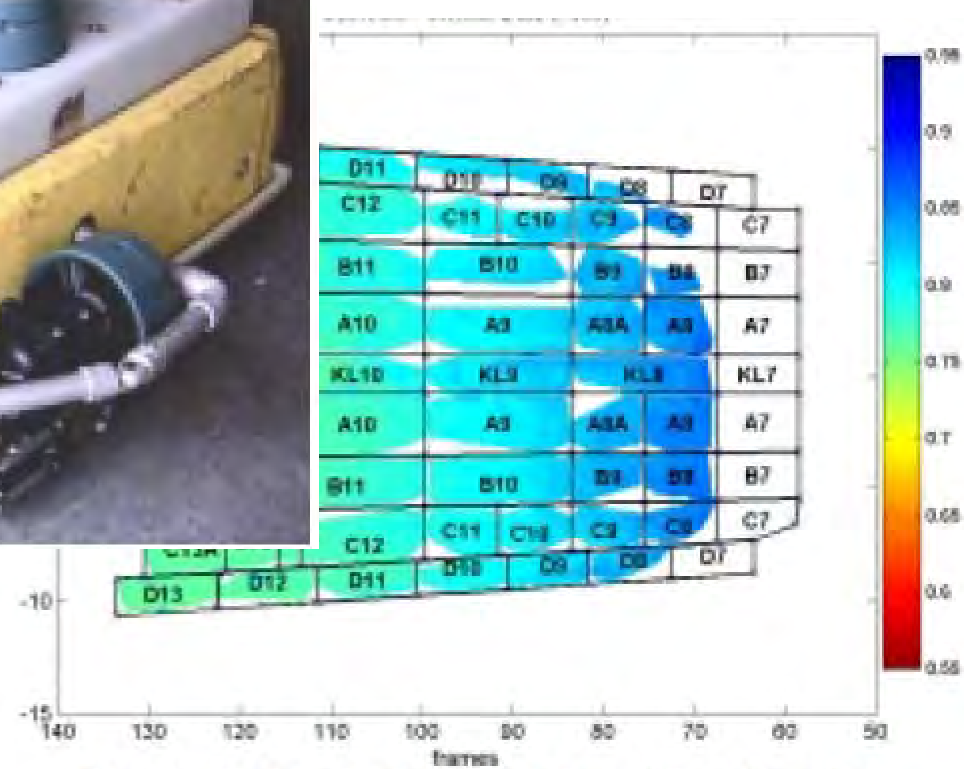
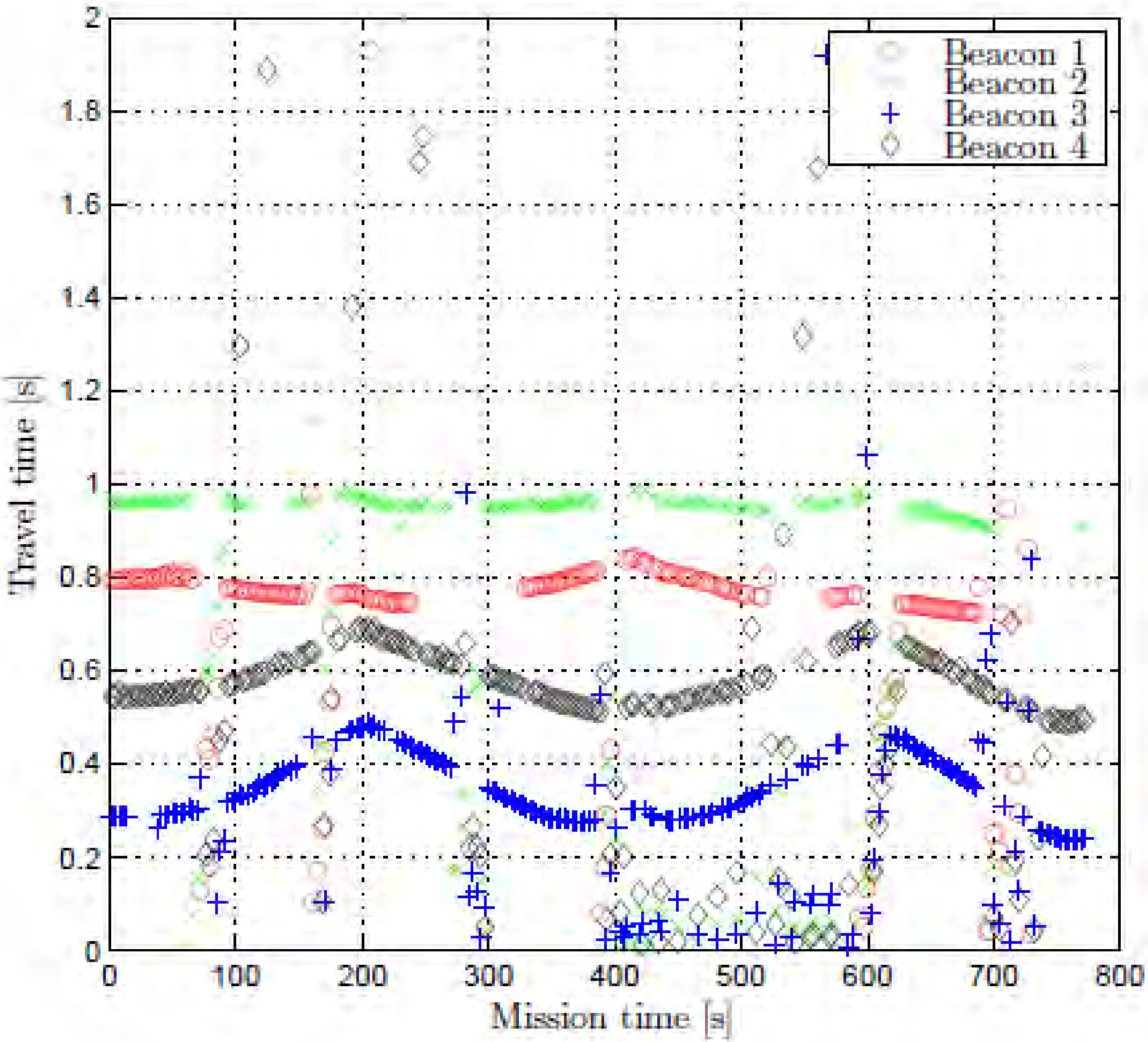


Fig. 6: Cathodic Potential Data Visualization

Nav: 300kHz LBL

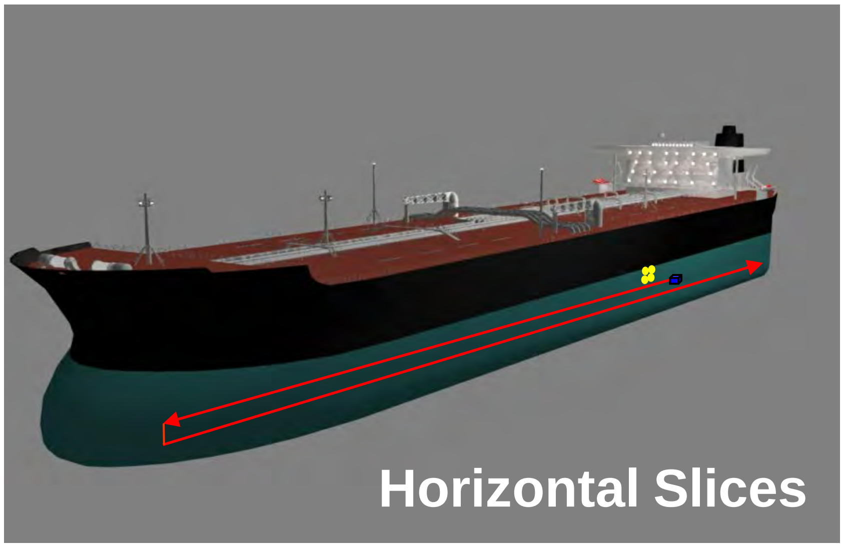


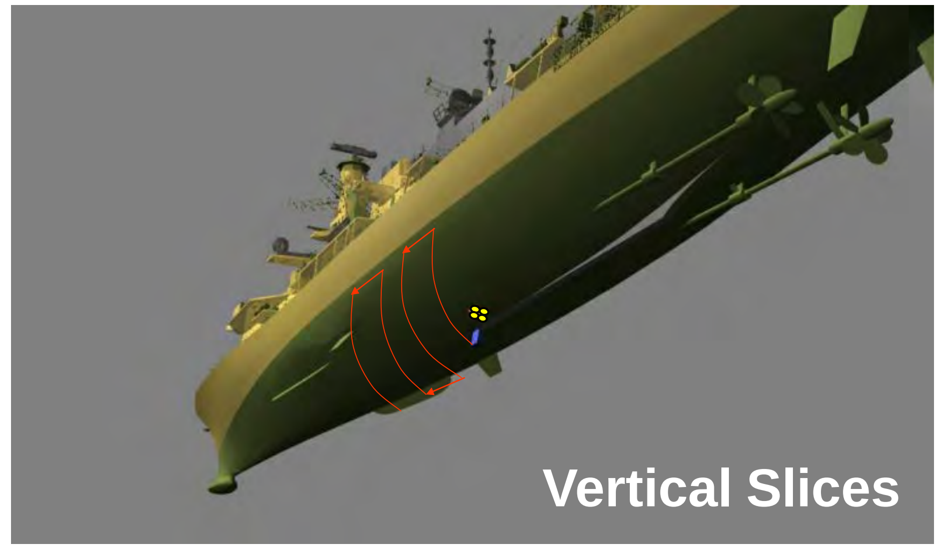
Four transponders and a moving vehicle in a long-baseline configuration; shown are travel times, which encode distance:
c ~ 1500m/s

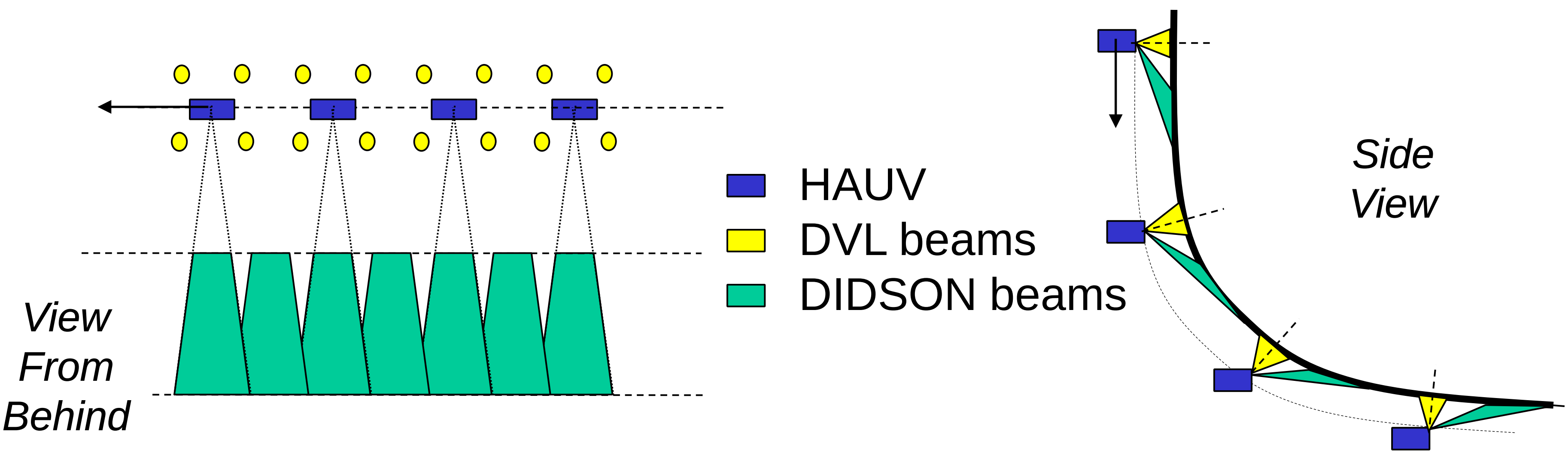
Long-Baseline Acoustic Navigation – flyers and holidays!

Image from Bahr 2009

Ship Inspection Strategies – Open Areas

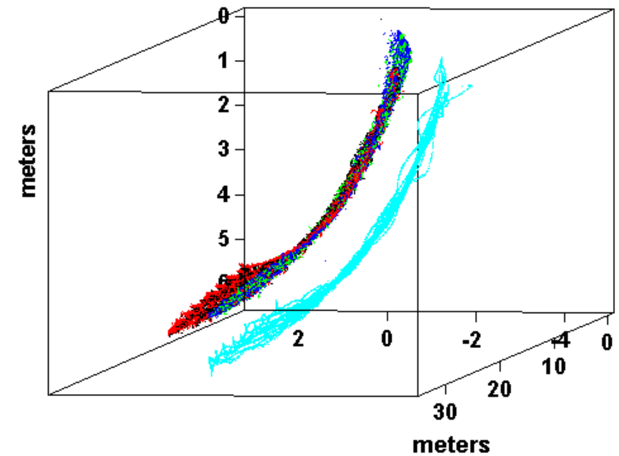


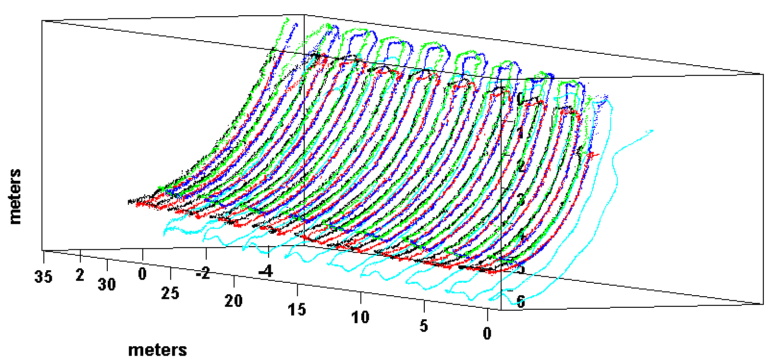


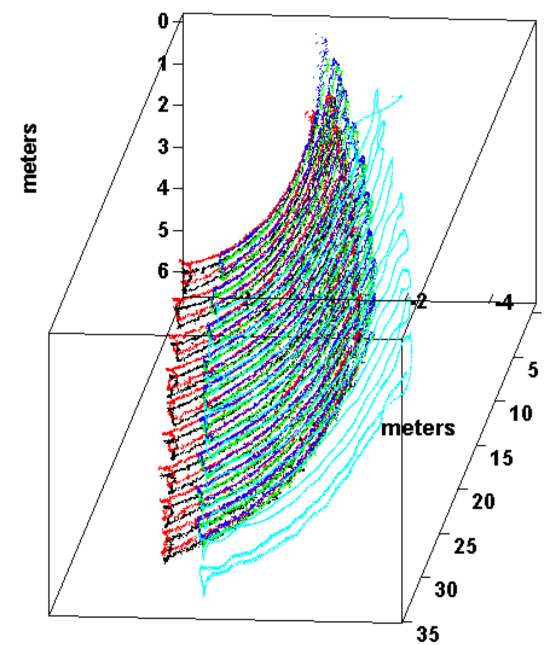


Long Vertical Survey

- Feb. 2nd, 2006
- Operator in trailer + RHIB
- FO tether + WiFi
- 34 m X 8 m, 2 m spacing
- 31 minute long survey
- DIDSON:
  - Automatic aiming
  - Real-time display
  - Logging both:
    - In the vehicle
    - In the topside computer

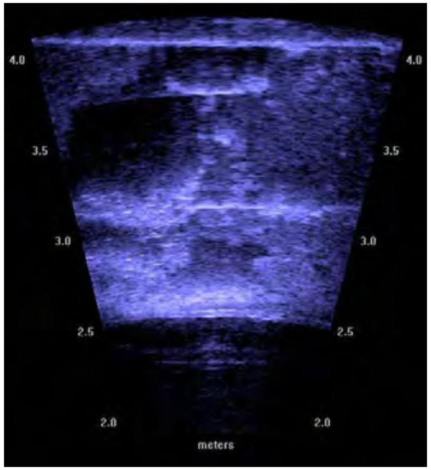
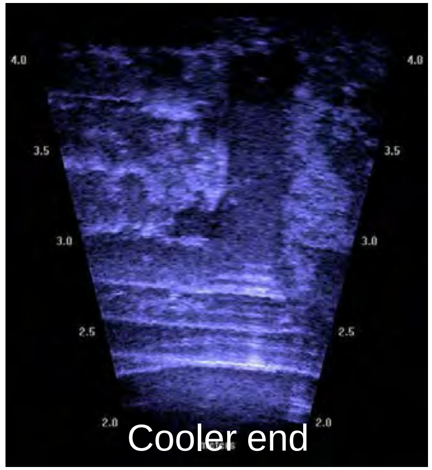


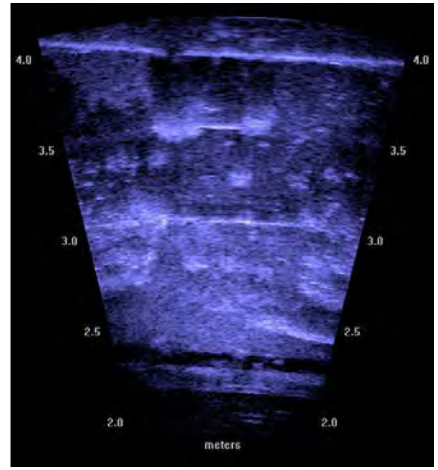
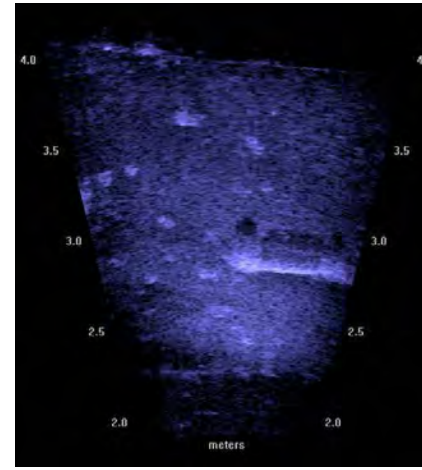
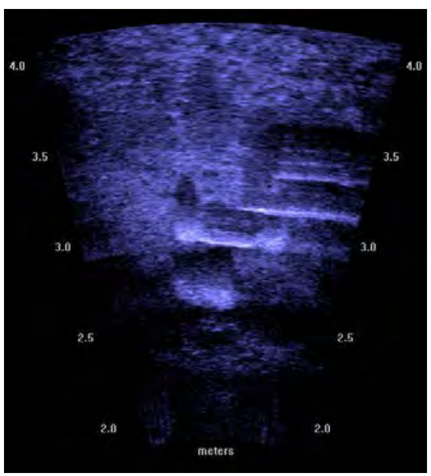
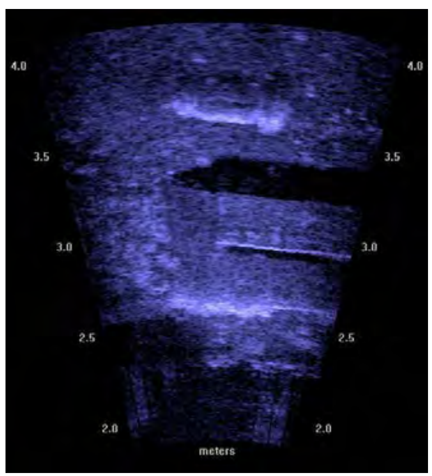
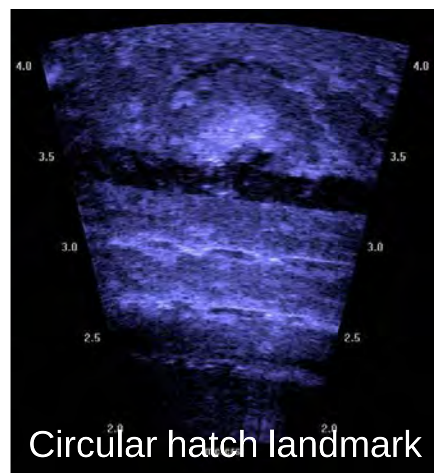


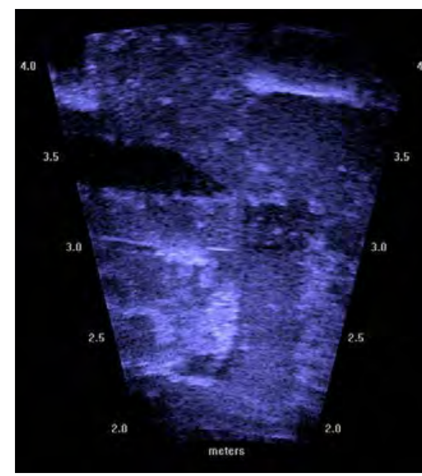


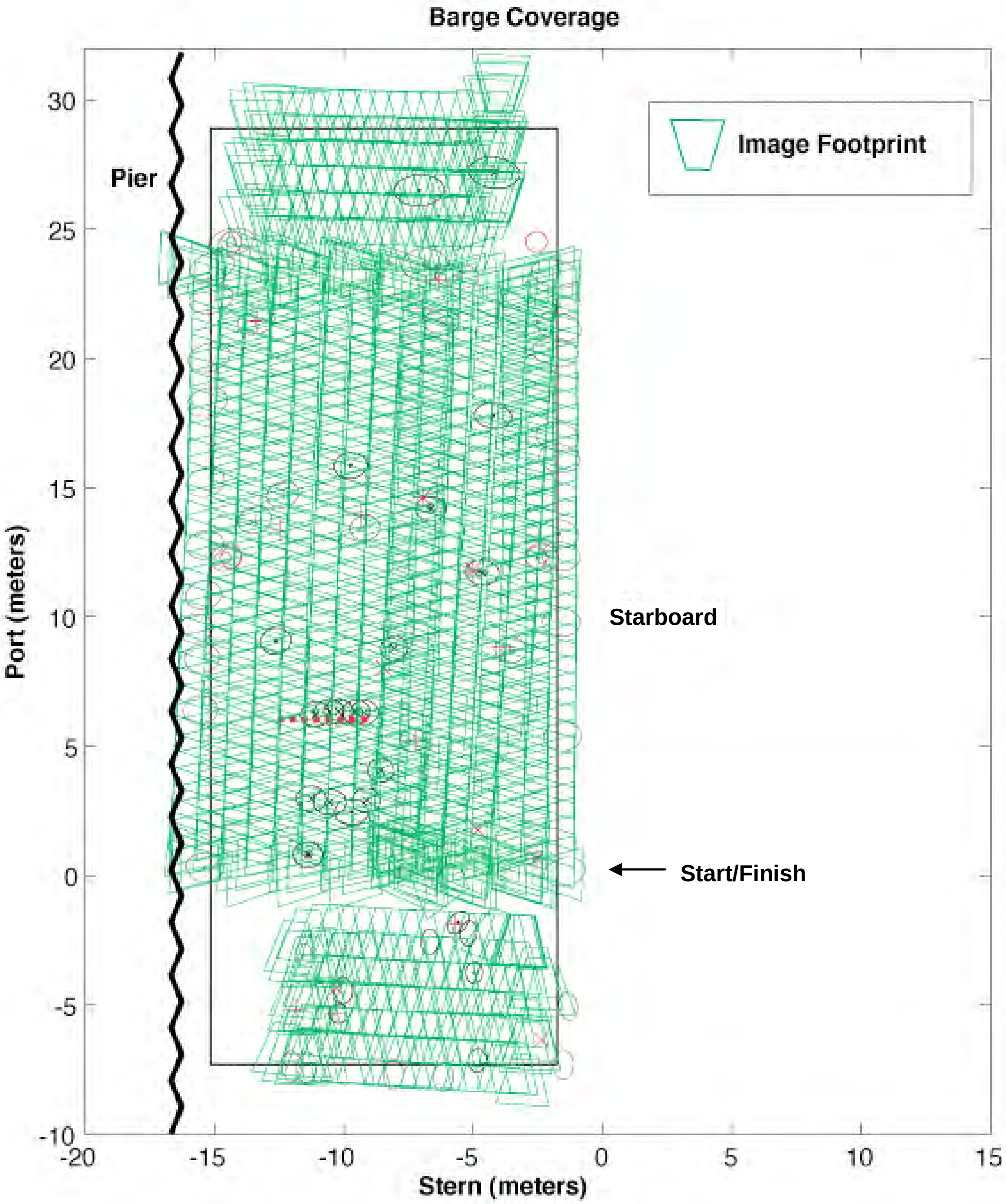
J. Vaganay, Bluefin

Typical Didson Imagery

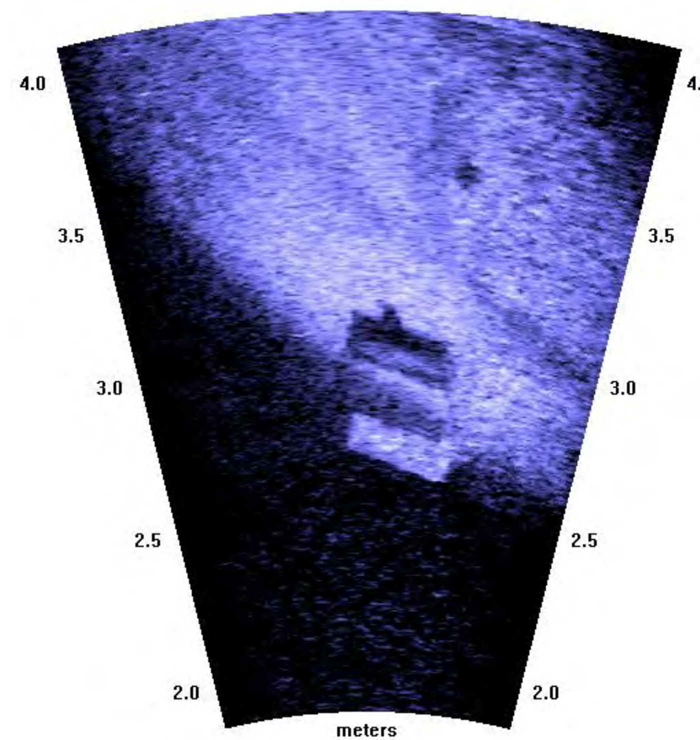





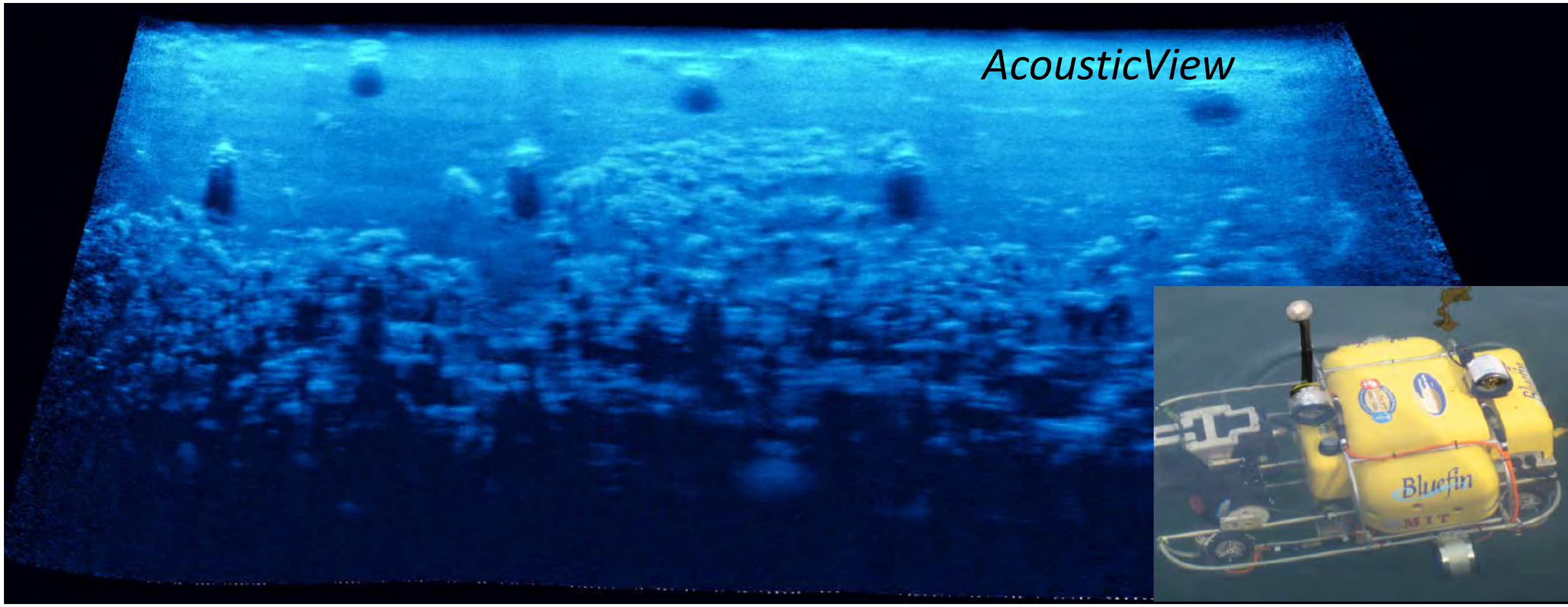


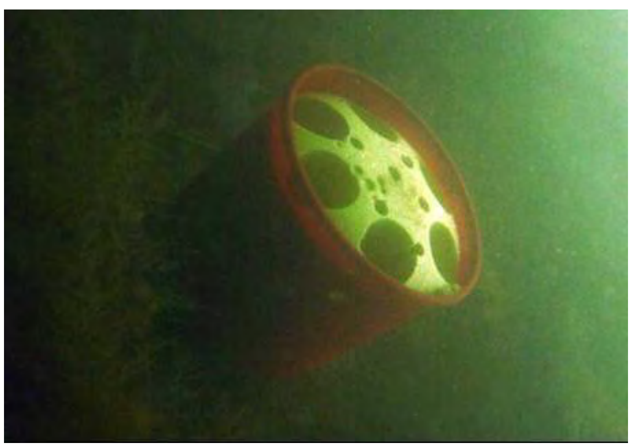
Bottom coverage shown with DIDSON footprints; dataset first used for SLAM (ESEIF)



M. Walter, MIT

AUVFest 2008: Map-Building and Mosaicking on the *USS Saratoga*



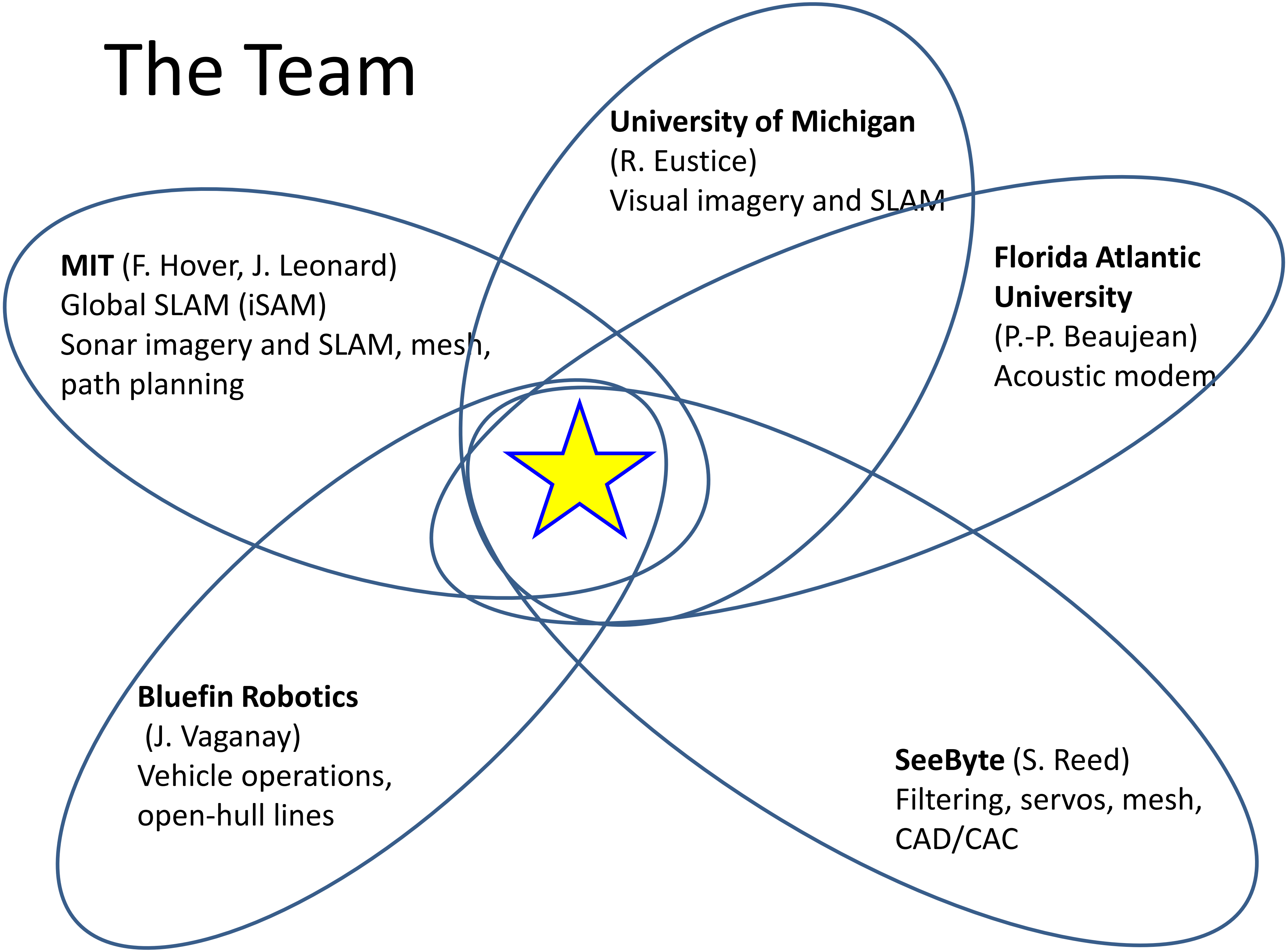


- Nine bucket targets were planted on the hull of the *Saratoga* in rows of three (the bottom row was obscured by biofouling)

Why Ship Hull Inspection is not necessarily a **"planning under uncertainty"** robotics problem

- Structure to be inspected is partially known: CAD models, preliminary scans, human knowledge, etc.
- For the foreseeable future, humans will watch and be close by
- Navigation is not completely dependent on the environment; odometry and heading might be quite good over short time frames
- 100% coverage is the goal – does exploration achieve it?
- Sensor input is already difficult enough to interpret!

The Team


University of Michigan
(R. Eustice)
Visual imagery and SLAM
MIT (F. Hover, J. Leonard)
Global SLAM (iSAM)
Sonar imagery and SLAM, mesh, path planning
Florida Atlantic University
(P.-P. Beaujean)
Acoustic modem
Bluefin Robotics
(J. Vaganay)
Vehicle operations, open-hull lines
SeeByte (S. Reed)
Filtering, servos, mesh, CAD/CAC

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   Sonar and visual imagery both have a key role in building maps and navigating with them

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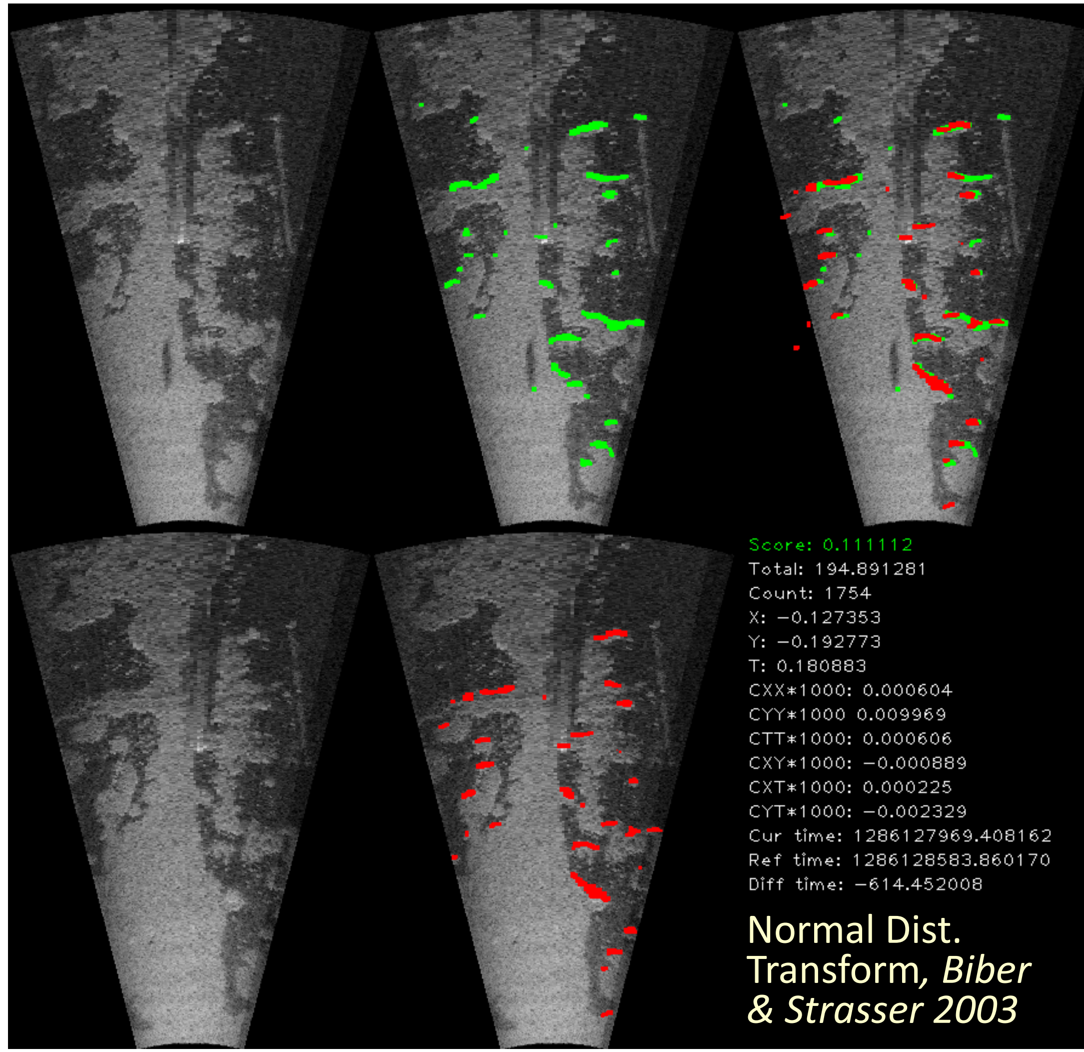
   Guaranteed approximation algorithms to a covering tour problem can provide practical plans quickly

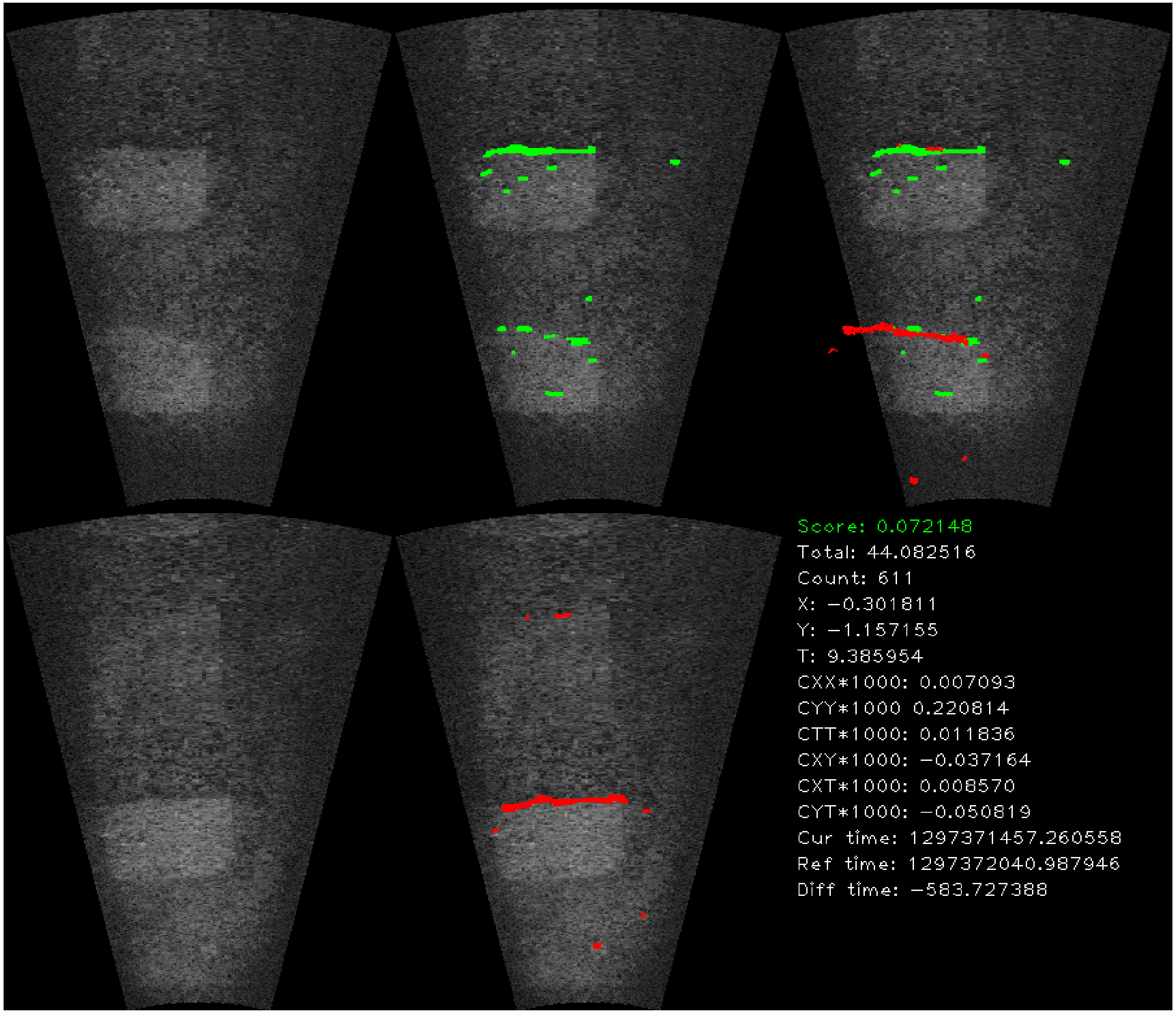
“Cake” Target: Visual vs. Sonar Imaging for Hull-Relative Navigation in Non-Complex Area

East Coast ports RARELY have good water clarity; this is the best possible view!



H. Johannsson, MIT

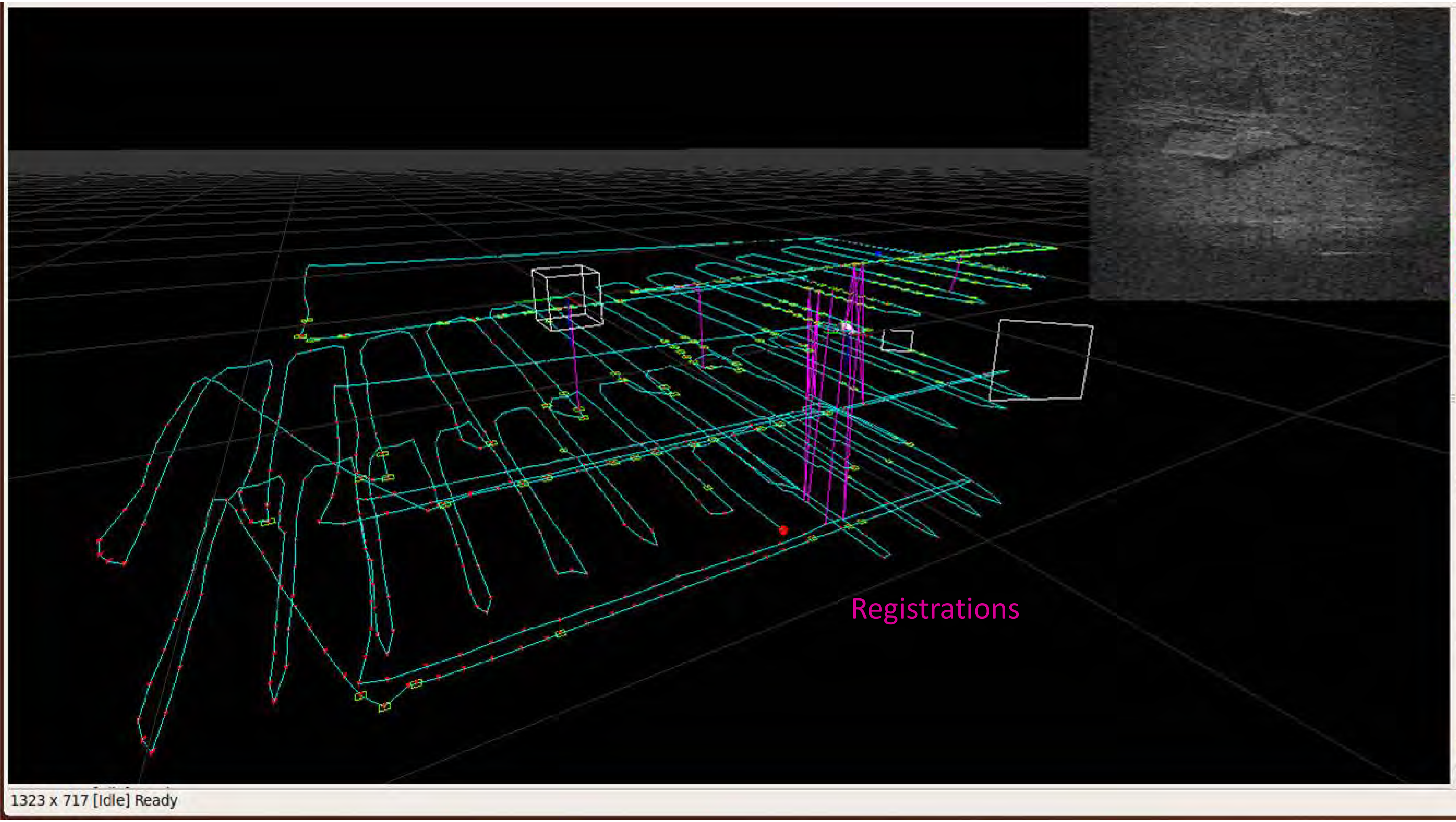
Ship Features for Hull-Relative Navigation



H. Johannsson, MIT

Time as a third axis

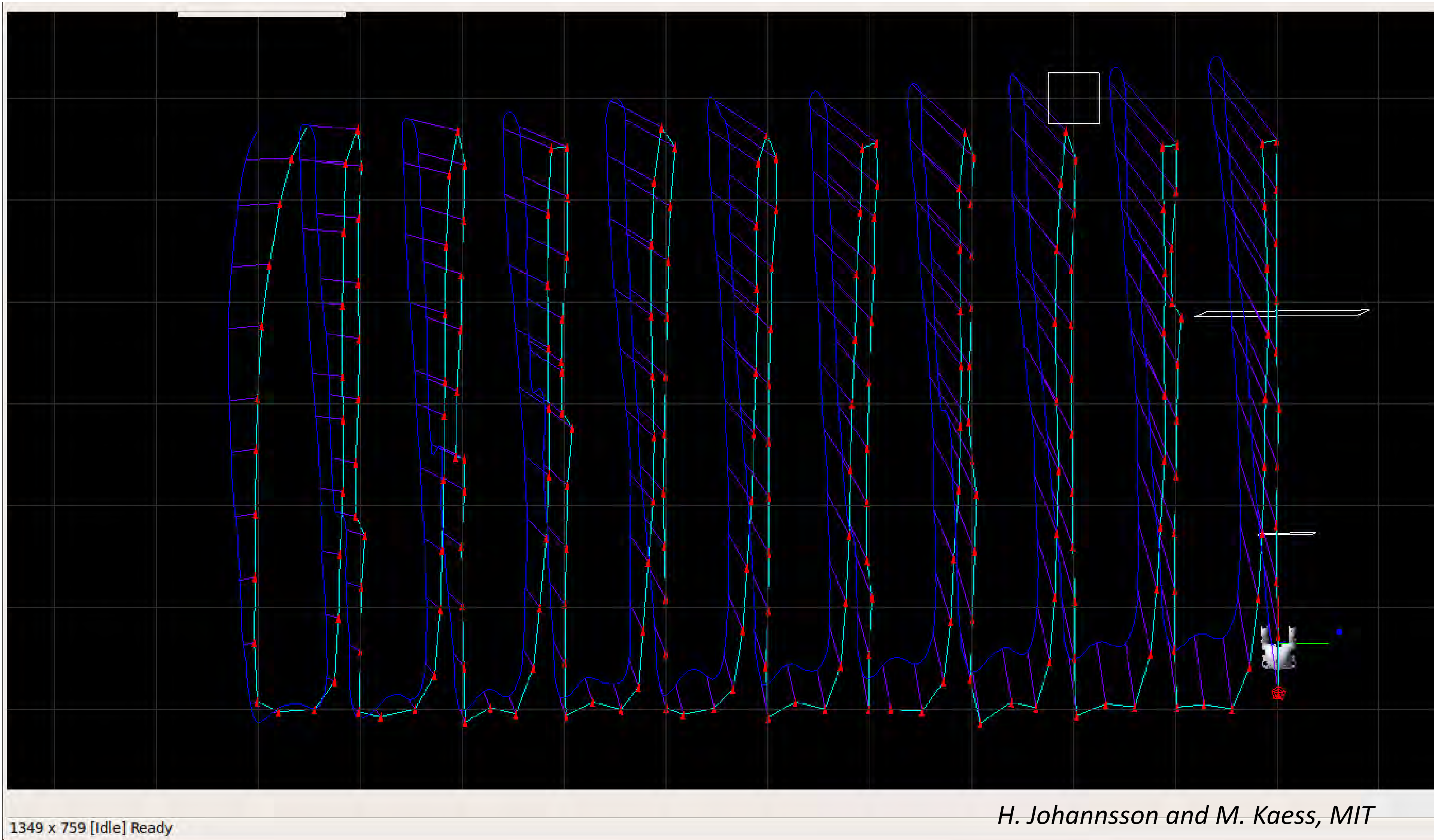
Charles River, Boston



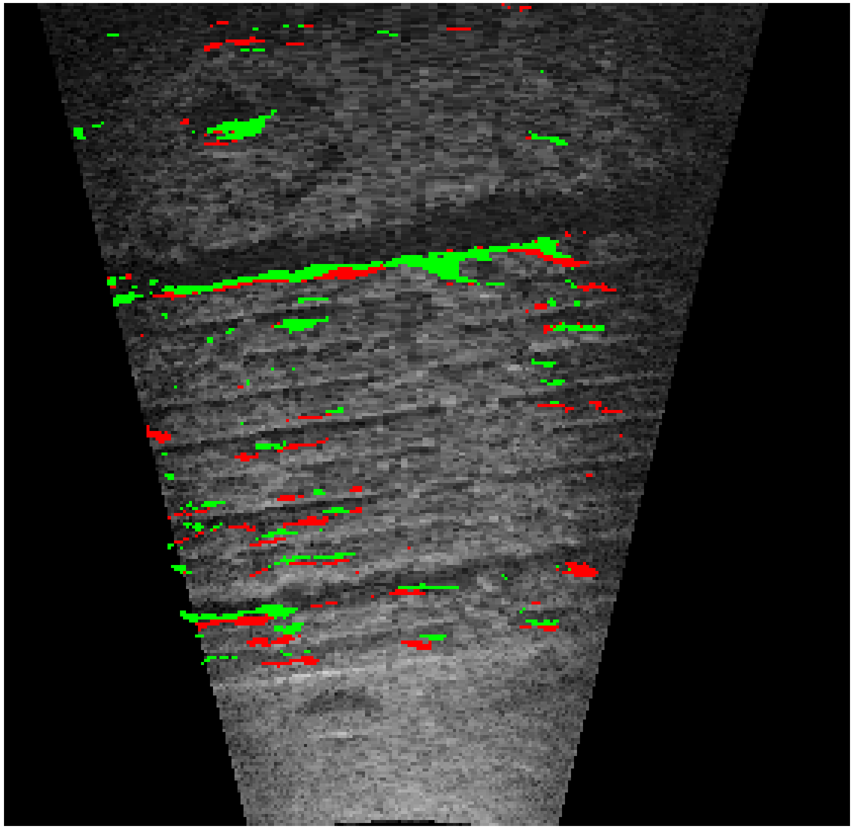
H. Johannsson and M. Kaess, MIT

Correct vs. Dead-Reckoned Path

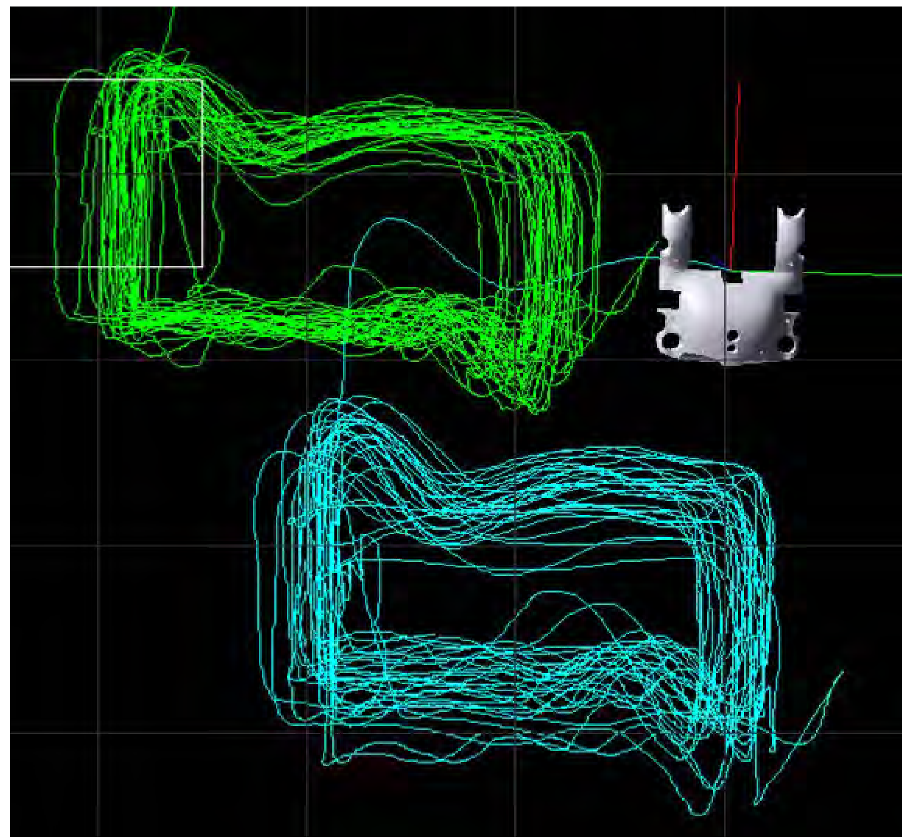
Charles River, Boston



H. Johannsson and M. Kaess, MIT



Closing the Loop:
HAUV1B on
King Triton,
East Boston, MA

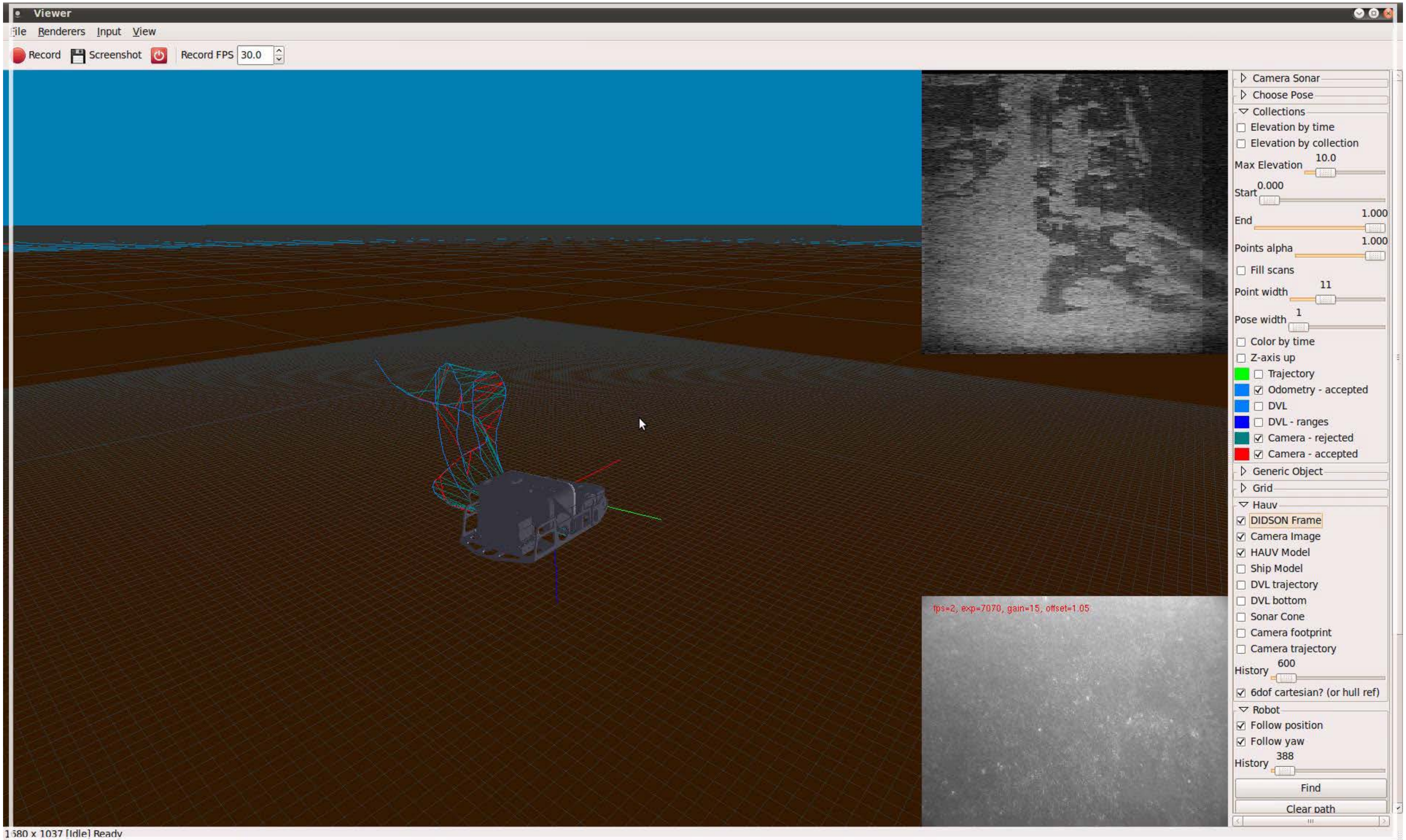


Representative registration pair, showing cooling channels and biofouling

Dead-reckoned path over one hour vs. feature-based nav.

H. Johannsson and M. Kaess, MIT

Vision SLAM from Ryan Eustice, UMichigan San Diego, CA Feb 2011



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National Geographic
May 2008

Stainless Steel Propeller of an Ice-Breaker: Complex!

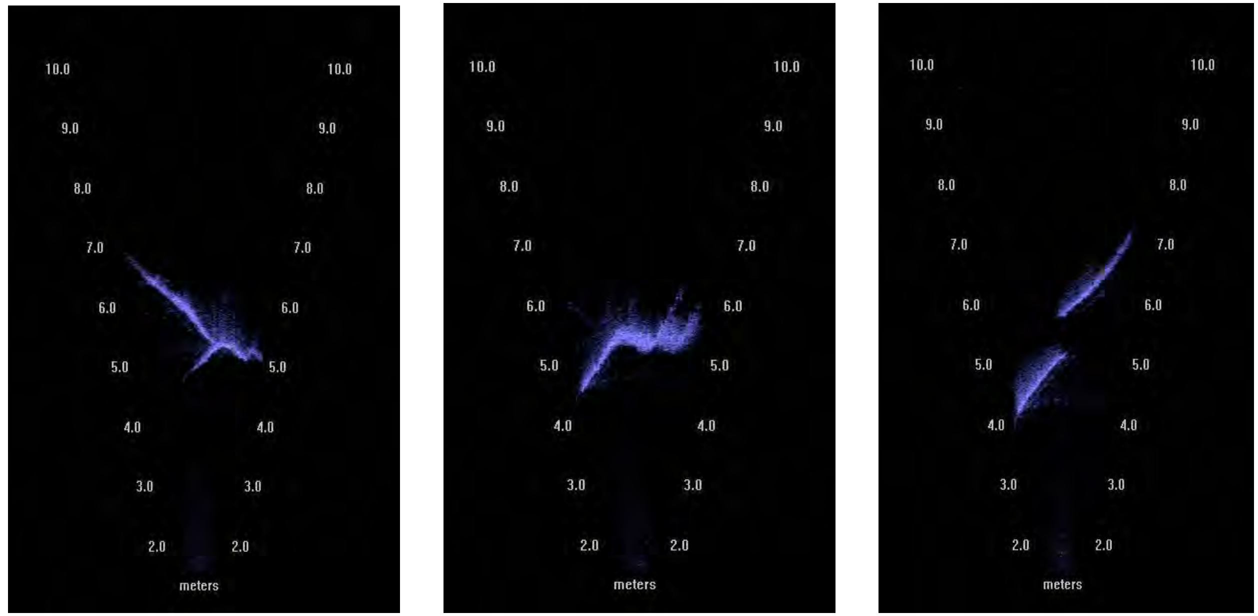
Obtain a set of images that covers the structure, in minimum time.

Combination of classic traveling salesman and set cover problems, both known to be NP-hard →

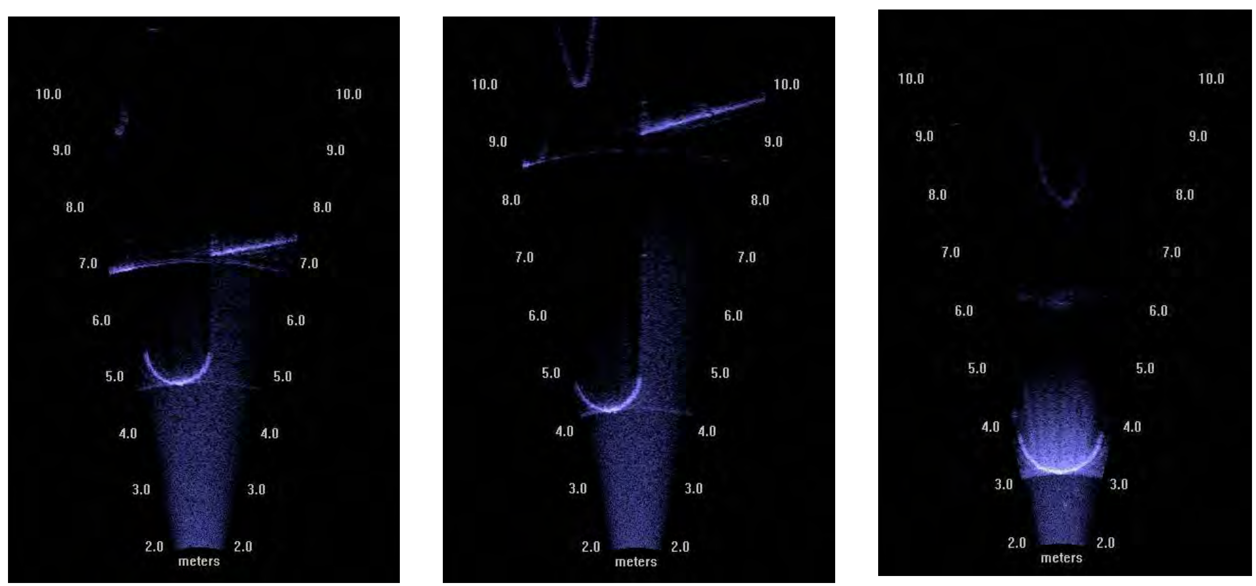
Seek guaranteed approximation factors in polynomial time, for on-site use

DIDSON Profiling Sonar Shows Sections Only

Surveying the propeller of a 300-meter Military Sealift Command Ship (propeller about 4 meters in diameter)

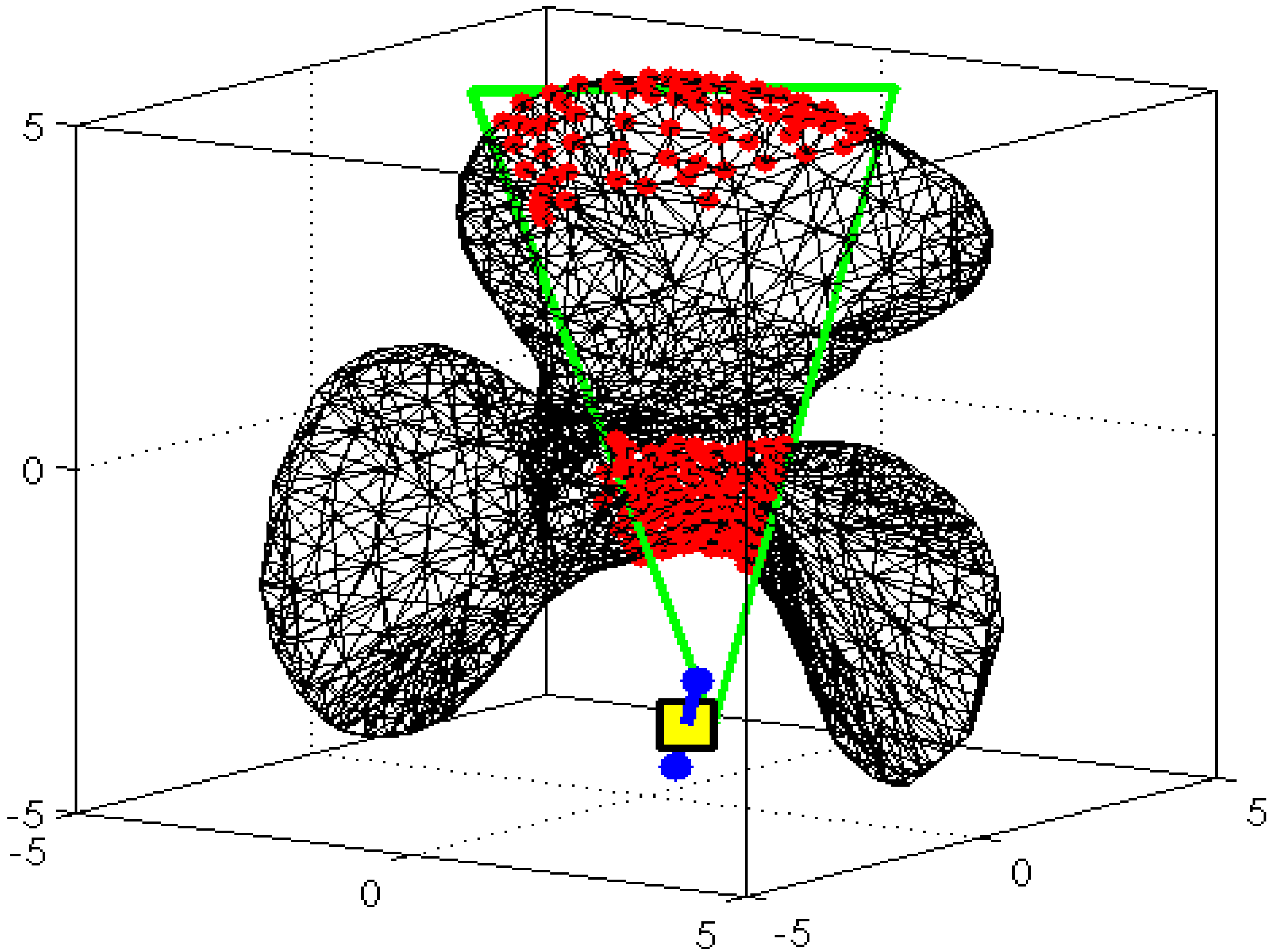


Surveying a shaft of the same ship (shaft about 1 meter in diameter)



Oh say can you see?

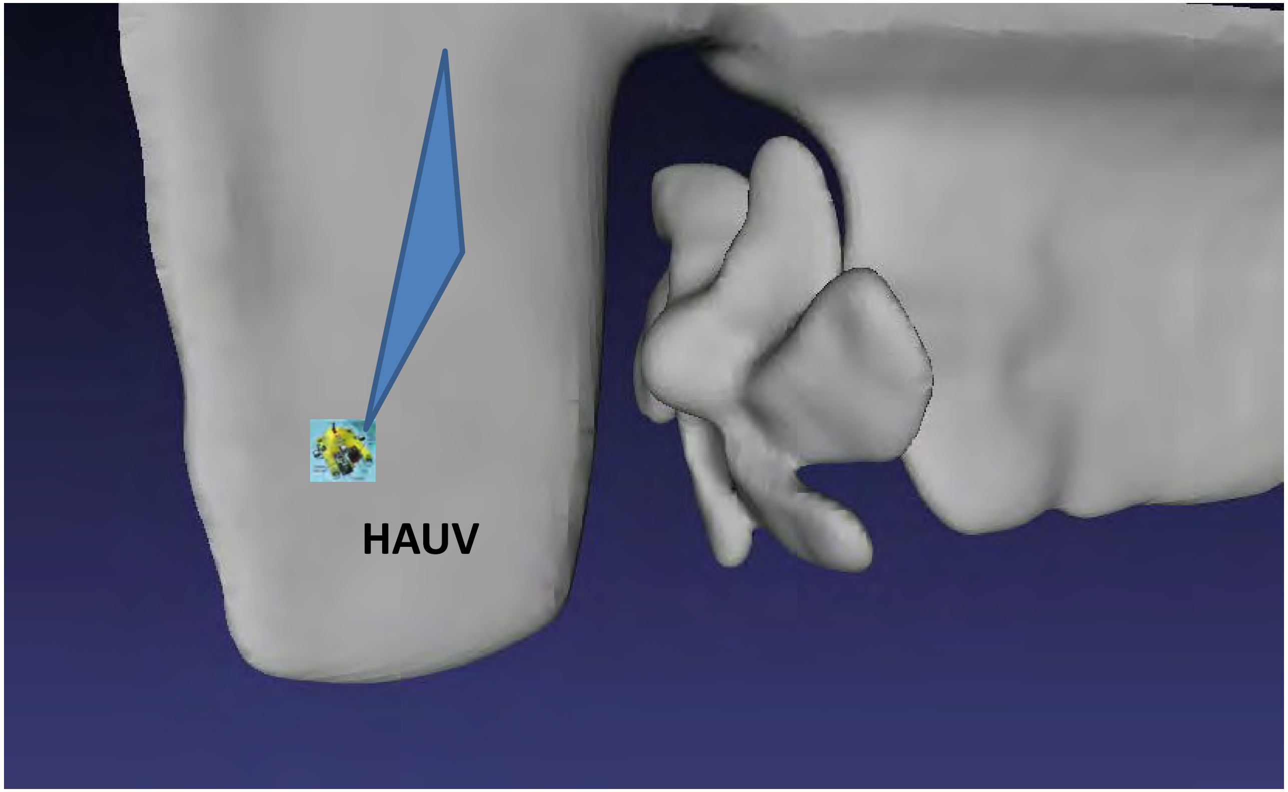
Not your 2D coverage problem

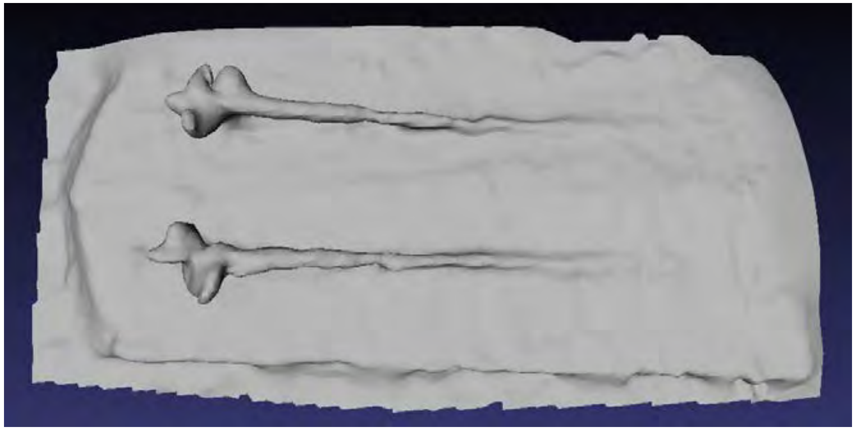


B. Englot, MIT

Watertight mesh on a 7m prop for 183m *USS Curtiss*, from coarse profiling sonar

Feb 2011, San Diego

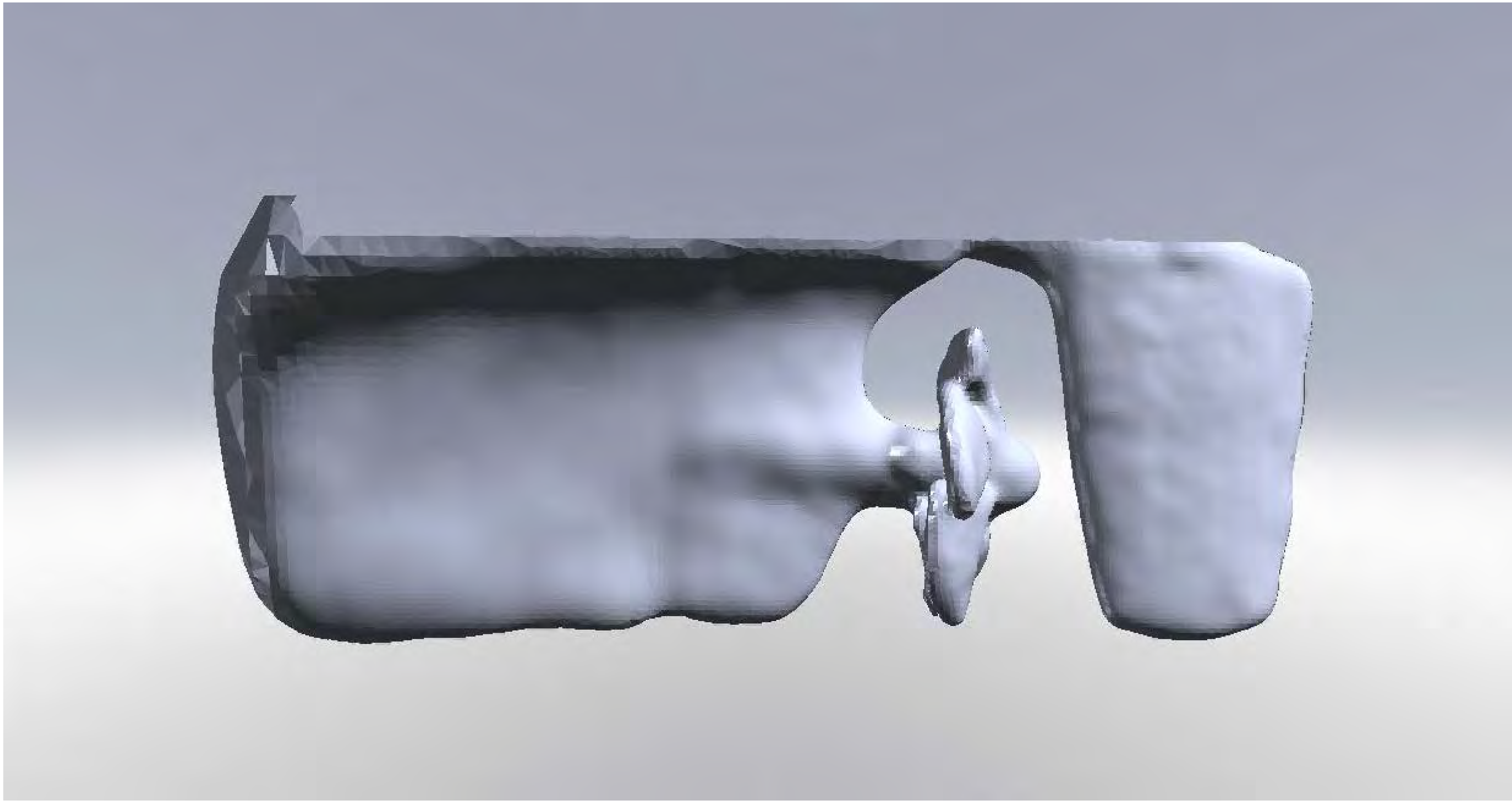




1m props on a 28m vessel

B. Englot, MIT

Watertight mesh on a 21-foot prop for 600-foot *USS Curtiss*, from profiling sonar Feb 2011, San Diego

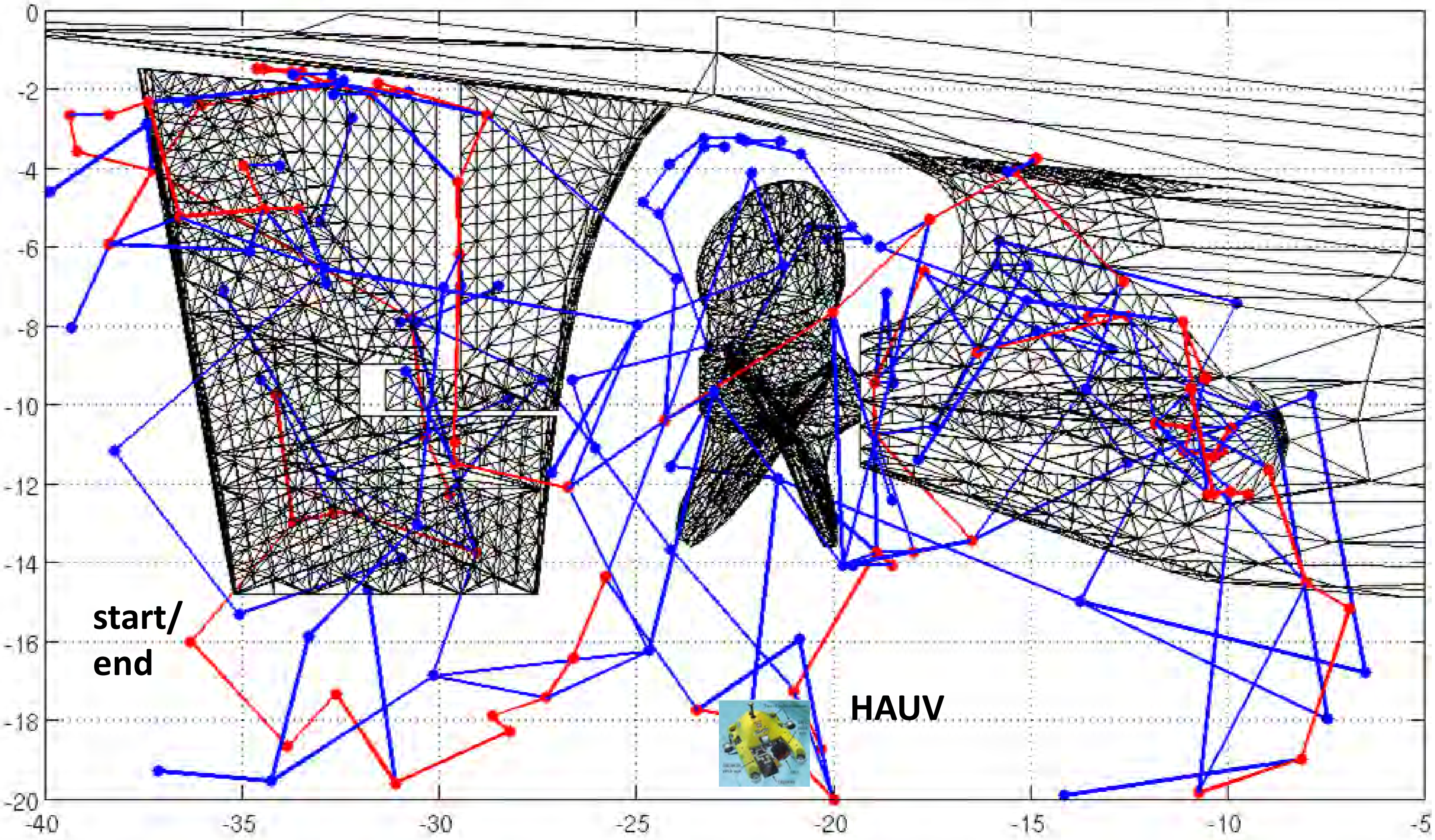


45 min vehicle run-time, 10Hz sampling of range scans
25k points subsampled from >>1m

B. Englot, MIT

An Outcome of Sampling-Based Planning in 5D Configuration Space, 4000 Targets; ~30% “efficient”

Integer programming solution to RPP with set cover constraints



B. Englot, MIT

Some Multi-Goal Planning Works & Context

Select goals in *C* to achieve coverage or reconstruct an object(s), *e.g., Danner & Kavraki 2000, Easton & Burdick 2005*

Given goals in *C*, find feasible path of minimum cost that visits them, *e.g., All-Pairs PRM (Spitz & Requisha. 2000), Lazy MST (Saha et al., 2006), Ant Colony Opt. (Englot & Hover, 2011)*

Given targets, covering goals, and feasible edges, find min-cost path (VPP), *e.g., Scott et al. 2003, Wang et al. 2007*

We consider the whole design problem:
Targets and obstacles given – i.e., the structure only

Multi-Goal Path Planning is Combinatorial and We Need O(100,000) targets → *Cost Explosion*

Approximate the Set Cover & TSP combined problem with the <u>Tour Cover</u> (TC) of Arkin, Halldorsson, and Hassin (1993):

Given a graph with weighted edges, compute the minimum-cost tour that is a vertex cover

Step 1: Map smallest edge weights onto nodes, and solve the weighted vertex cover (WVC)

Step 2: Condense the graph around the edges that defined the WVC

Step 3: Solve a reduced TSP, and then expand out the condensed edges

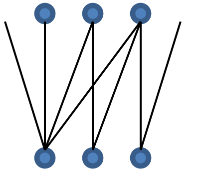
$$APX_{TC} \leq 2\, APX_{WVC} + APX_{TSP}$$

A Modification to the TC Achieves Practical Coverage Planning

- Insert *Step 0: Use sampling to generate a pose cover of discrete mesh targets; interpret targets as links in configuration space*

- Replace condensing step (2) with direct edges if shorter

- Enforce a 2-cover bipartite graph: $\boldsymbol{APX_{WVC} = 1}$, in LP time



- Use Christofides approximation: $\boldsymbol{APX_{TSP} \leq 3/2}$, in $|V|^3$ time

→ $\boldsymbol{APX_{TC} \leq 3.5}$ is achievable formally; but *Step 0* does not address performance of the cover.

How will it do?

Some Choices on the Sampled Cover

Regular lattice poses

Random poses on manifold

Entirely random poses

Revise and refine cover

Build cover on the fly; no revisions

Etc.

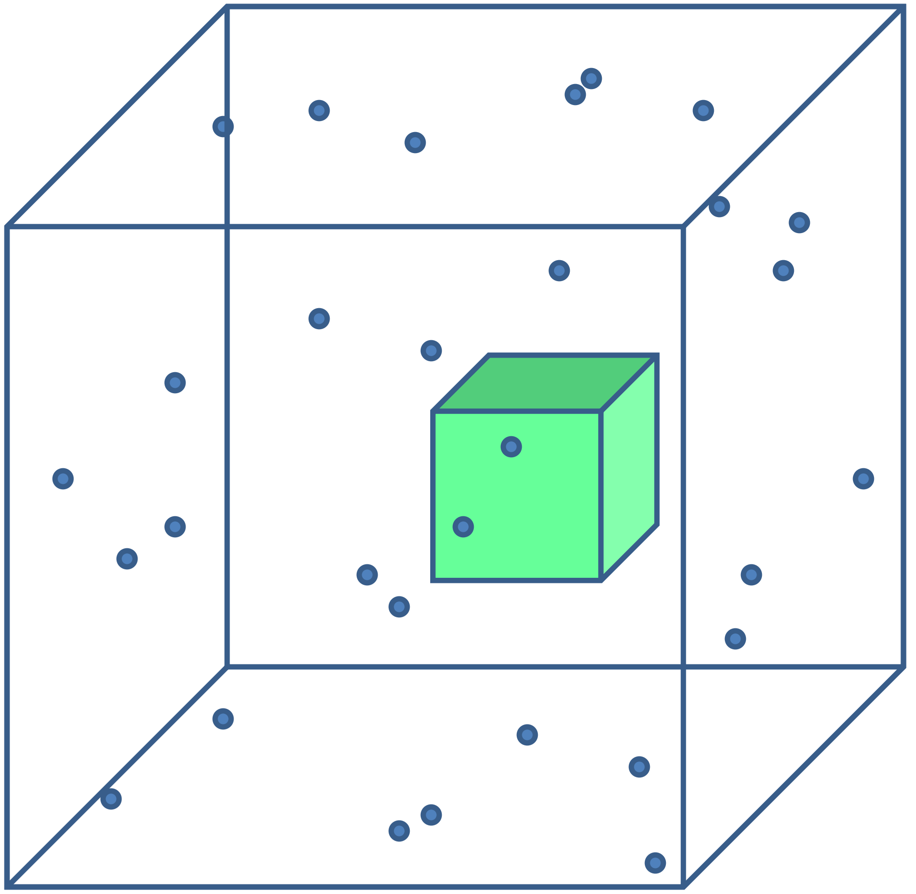
A Computational Experiment:

3D cubic domain with no obstacles

Uniformly distributed point targets

Vehicle pose [X , Y , Z, hdg]

Sensor footprint is a cube with 1% of domain volume



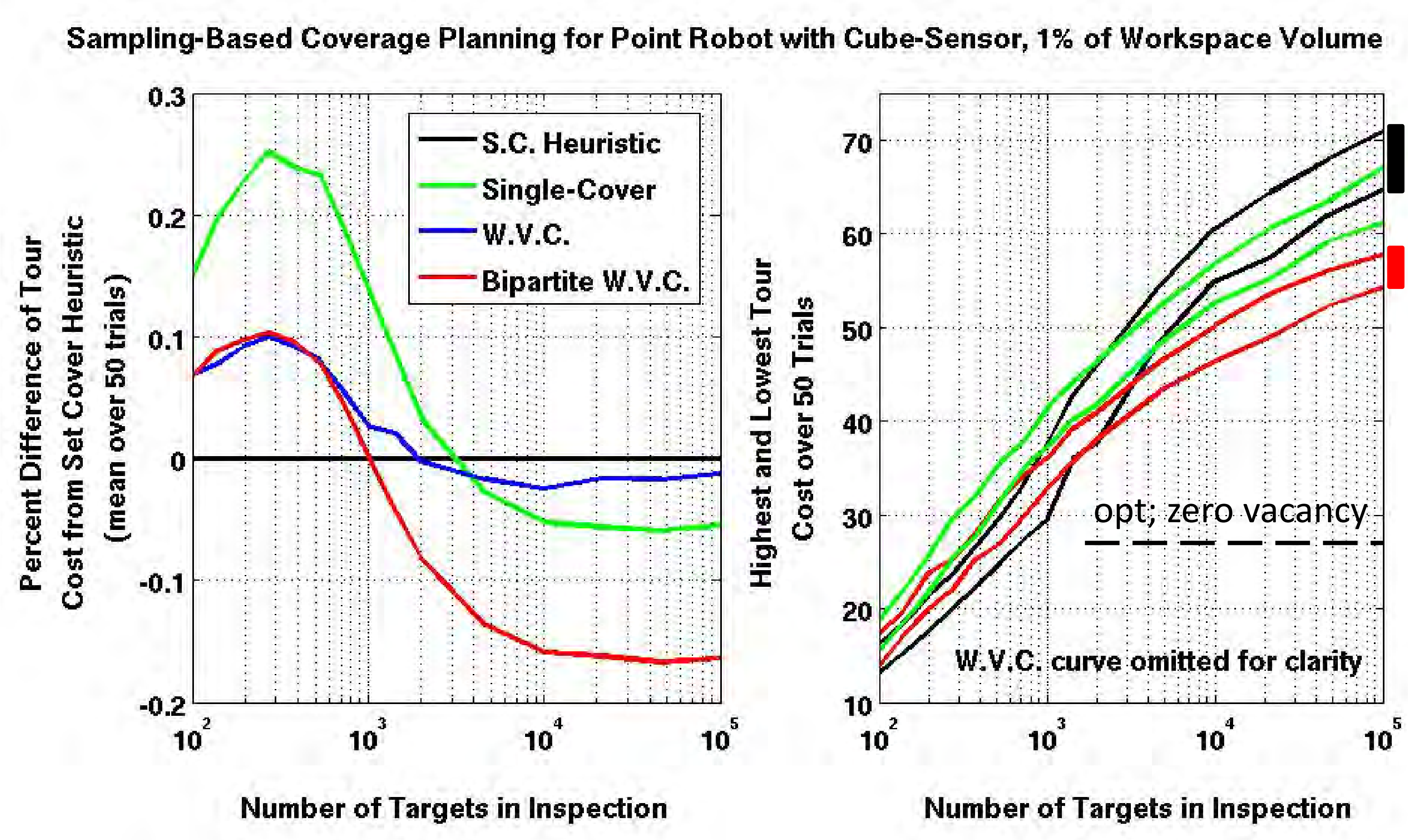
For initial graph construction, consider options (all polynomial time):

A.	**<u>Set Cover Heuristic</u>: Take first available cover, keeping all poses that see any new target (not a 2-cover); links accrue.** **SC via rounding LP has $APX_{SC} \leq f$ (highest multiplicity of sightings)**	**BASELINE**
B.	**<u>Single Cover</u>: Sample until every target is attached to a pose.** **No further graph work – each pose is visited.**	**DUMB?**
C.	**<u>2-Cover WVC</u>: Take first available 2-cover; reject extra links & poses.** **WVC via rounding LP has $APX_{WVC} \leq 2$**	
D.	**<u>2-Cover Bipartite WVC</u>: Take first available bipartite 2-cover; greedy partition heuristic to maximize targets hit; reject extra links & poses.** **WVC via LP is exact $APX_{WVC} = 1$**	**HIGHLY STRUCTURED**

and then solve TSP with Christofides

Computational Experiment

Result: *Bipartite WVC becomes ~15% better than baseline at high N;*
and TOTAL efficiency at 100,000 targets is about ***0.50***
Single-cover becomes ~5% better than baseline at high N



In-Water Ship Hull Inspection with Autonomous Robots

1. The Objective and its Components

   The task forms a rich and important robotics problem that spans several disciplines

2. Non-complex areas: Feature-Based Nav

   Sonar and visual imagery both have a key role in building maps and navigating with them

3. Complex areas: Feature-Based Planning

   Guaranteed approximation algorithms to a covering tour problem can provide practical plans quickly

Hard Open Problems Relevant to the Marine Inspection Missions

- *Better Sensors and Comms*

- 3D SLAM and real-time control on complex structures

- The sealion problem: two minutes